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THESIS

SIMULATION ANALYSIS OF UNMANNED AERIAL VEHICLES (UAV)

by

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June 1999

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Warfighting Commanders in Chief (CINCs) have identified a need to provide lower-level tactical units (especially brigades) with real-time responsive Reconnaissance, Surveillance, and Target Acquisition (RSTA). There are many unanswered questions, some of which are: "Which UAV system best suits the needs of the brigade commander?", "How many UAVs does a brigade need?", and "What are the Tactics, Techniques, and Procedures (TTP) for the use of this new system?" This thesis demonstrates the ability to design a small high resolution simulation which can be used to answer these questions. The simulation can be used throughout the acquisition process, and potentially beyond.

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SIMULATION ANALYSIS OF UNMANNED AERIAL VEHICLES (UAV)

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ABSTRACT

Warfighting Commanders in Chief (CINCs) have identified a need to provide lower-level tactical units (especially brigades) with real-time responsive Reconnaissance, Surveillance, and Target Acquisition (RSTA). There are many unanswered questions, some of which are: "Which UAV system best suits the needs of the brigade commander?", "How many UAVs does a brigade need?", and "What are the Tactics, Techniques, and Procedures (TTP) for the use of this new system?" This thesis demonstrates the ability to design a small high resolution simulation which can be used to answer these questions. The simulation can be used throughout the acquisition process, and potentially beyond.

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the available time, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification and validation is at the risk of the user.

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TABLE OF ABBREVIATIONS

AO	Area of Operations
AWE	Advanced Warfighting Experiment
BDA	Battle Damage Assessment
BFV	Bradley Fighting Vehicle
CDF	Cumulative Distribution Function
CIA	Central Intelligence Agency
CINCs	Commanders in Chief
DAWE	Division Advanced Warfighting Experiment
DFR	Decreasing Failure Rate
DMSO	Defense Modeling and Simulation Office
DTO&E	Director, Operational Test and Evaluation
ETOS	Effective Time on Station
FIFO	First - In, First - Out Queue
GCS	Ground Control Station
IDA	Institute of Defense Analyses
IFR	Increasing Failure Rate
IID	Independent and Identically Distributed
IPPD	Integrated Product Process Development
LDT	Logistics Delay Time
MAF	Mission Affecting Failure
MASS	Military Aircraft Sustainability Simulation
MNS	Mission Need Statement
MOE	Measure of Effectiveness
MOP	Measure of Performance
Mpt	Mean Preventive Maintenance Time
MTBMAF	Mean Time Between Mission Affecting Failures
MTTR	Mean Time to Repair
NMC	Non-Mission Capable
non-MAF	non-Mission Affecting Failure
NTC	National Training Center
OPTEMPO	Operational Tempo
ORD	Operational Requirements Document
PDF	Probability Distribution Function
RMA	Revolution in Military Affairs
RSTA	Reconnaissance, Surveillance, Targeting and Acquisition
SBA	Simulation Based Acquisition
STEP	Simulation, Test and Evaluation Process
TRADOC	Training and Doctrine Command
TT	Turn Time
TTP	Tactics, Techniques and Procedures
TUAV	Tactical Unmanned Aerial Vehicle
UAV	Unmanned Aerial Vehicle
UAVSim	Unmanned Aerial Vehicle Simulation

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EXECUTIVE SUMMARY

In 1996, General John M. Shalikashvili, former Chairman of the Joint Chiefs of Staff, released Joint Vision 2010, which outlines a conceptual template for the evolution of the Armed Forces of the future and a pending Revolution in Military Affairs (RMA). A key element of this evolution and revolution focuses on the exploitation of "information-age" technological advances. More lethal weapon systems, new sensor packages, and improved information transfer are now possible because of increasingly sophisticated technologies. These new technologies are so powerful that they are revolutionizing the art of warfare for our Armed Forces.

One of these new technologies is the unmanned aerial vehicle (UAV). The Army's Training and Doctrine Command (TRADOC) is examining the impact of this new technology through Advanced Warfighting Experiments (AWE). However, there are several questions that must be answered as the Army moves toward acquisition and fielding. Simulation is an important decision aid in these efforts. Unfortunately, many traditional simulation models are not robust enough to reflect many of the attributes of this new system. In addition, these simulations are difficult to modify and require a significant amount of time and money to modify.

This thesis demonstrates the ability to design a small high resolution simulation which can be used to answer questions about the performance of UAV systems that arise before, during, and after the acquisition process. Furthermore, this thesis establishes a basis for further research in the analysis of UAV performance and effectiveness.

The simulation developed was written in Java and uses the discrete-event simulation library Simkit which is available from the Naval Postgraduate School. The model allows

analysts to answer specific questions about the performance of UAVs. The structure of the model is based on event graphs in which nodes represent events and their connecting arcs represent the passage of time. This simulation is a stochastic, event-step model.

This work demonstrates the ability to use the model to determine the values of measures of performance (MOP) and the effect of modifying performance parameters. Threshold and objective values specified in the Operational Requirements Document (ORD) are examined for their adequacy for the acquisition of systems. The point of diminishing return is determined as well and the benefit of structural changes. Lastly, the ability for the analyst to perform analysis of alternatives is demonstrated. This allows for the comparison of existing and future UAV systems.

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I would like to express my thanks to Dr. Arnold Buss, Lieutenant Colonel David H. Olwell, and Lieutenant Colonel Charles H. Shaw, III. Without their broad knowledge in the areas of Simulation Based Acquisition (SBA) and Simulation Modeling, and Statistics this work could not have been completed. I also thank MG Scott Wallace for his experience tour support and his insight on a "real world problem," which was the catalyst for this work.

Finally, I would like to thank Lisa Pinkston, my devoted wife, who supported me throughout the challenges of this work.

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I. INTRODUCTION

A. GENERAL.

The past few years have been significant in the history of the United States Armed Forces. In 1996, General John M. Shalikashvili, former Chairman of the Joint Chiefs of Staff, released Joint Vision 2010, which outlines a conceptual template for the evolution of the Armed Forces of the future and a pending Revolution in Military Affairs (RMA). A key element of this evolution and revolution focuses on the exploitation of "information-age" technological advances. More lethal weapon systems, new sensor packages, and improved information transfer are now possible because of increasingly sophisticated technologies. These new technologies are so powerful that they are revolutionizing the art of warfare and marking a "strategic inflection point" for our Armed Forces [Ref. 1: p. 4]. Throughout history, employment of technologically superior equipment with the appropriate Tactics, Techniques, and Procedures (TTPs) and correct processes has been critical to the success of our forces [Ref. 2:p. 7]. Hence, "we must change in order to sustain current levels of excellence in the future" [Ref. 3:p. 1].

Information technologies and their impact on future military operations are an important theme throughout Joint Vision 2010. Our forces must attain "information superiority." Joint Vision 2010 defines information superiority as "the capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same" [Ref. 2:p. 16]. By achieving information superiority, our forces can achieve "dominant battlespace awareness," an interactive "picture" which yields accurate assessments of friendly and enemy operations within the

area of interest [Ref. 3:p. 13]. An apparent challenge is developing a means to attain dominant battlespace awareness in the midst of significant force structure modifications.

On 9 June 1998, General William Hartzog, then Commander of Training and Doctrine Command, put the Army's stamp of approval on the "new heavy division" design. The "new heavy division will still be the most lethal combat force in the world, even though it will have fewer soldiers and armored vehicles" [Ref. 4:p. 1]. Each maneuver brigade will lose a mixture of three companies' worth of armor and infantry vehicles, a significant decrease in combat power. However, the Army still expects this force to cover about three times more battlefield area than present day divisions. Technological advances in better sensors that will facilitate increased situational awareness are part of the Army's answer to this potential decrease in lethality and force protection.

Previous TTP did not require that all of a brigade commander's tanks and Bradley Fighting Vehicles (BFV) be engaged with the enemy. Most often, a commander would establish a screening or guard force as well as reserves because he was unsure of the enemy's location and his alternate avenues of approach. With better sensor packages and improved means of gathering intelligence, "you don't have to worry about that other direction anymore. Now a commander can focus all his energy in one direction" [Ref. 4:p. 2]. One of the many enabling technologies that will allow commanders to achieve better visibility of the battlefield and dominant battlespace awareness is the Tactical Unmanned Aerial Vehicle (TUAV). It is the structure and characteristics of the TUAV system that is the focus of this thesis.

The TUAV can now deliver this "picture" to the warfighter because of advances in technology and TTPs. Smaller, cheaper TUAV platforms and sensor packages, previously not available, now give the battlefield commander the capability to achieve a near-real time

picture of the battlefield. This information, processed accurately and efficiently, may allow the commander to achieve “dominant maneuver” and “precision engagements, ” two of the emerging concepts outlined in Joint Vision 2010. "Dominant maneuver" is the multidimensional application of information, engagement, and mobility capabilities to position and employ widely dispersed joint air, land, sea and space forces to accomplish the assigned operational tasks [Ref. 2:p. 20]. "Precision engagements" consist of a system of systems that enables our forces to locate the objective or target, provide responsive command and control, generate the desired effect, assess our level of success, and retain the flexibility to reengage with precision when required [Ref. 3:p. 21]. The TUAV is a combat multiplier and is essential to achieving information superiority and dominant battlespace awareness which will facilitate "dominant maneuver" and "precision engagements" [Ref. 5:p. 1].

B. PROBLEM DESCRIPTION.

UAV systems currently exist and have been employed in a number of military operations. However, these systems have primarily supported higher-level units and national agencies, such as Army Corps and the Central Intelligence Agency (CIA) [Ref. 6:p. 1]. In 1998, the Army began the process of acquiring a UAV for brigade level units with the submission of the Operational Requirements Document (ORD) for the Close Range – Tactical Unmanned Aerial Vehicle (CR-TUAV). There are numerous potential TUAVs from which to choose. Immediate questions of interest are: “Which TUAV best suits the needs of the brigade commander?”, “How many TUAVs does a brigade need?”, “What are the Tactics, Techniques, and Procedures (TTP) for this new system?”. The larger questions are: “How effective is a TUAV system as an integrated part of sensor-shooter links? ” and "How must current processes be modified to achieve maximum effectiveness?"

The answers to these questions could be obtained through extensive field testing and experimental training with prototypes; however, such an approach would require an overwhelming amount of money and time. A more practical solution is evaluation and analysis through simulation. In recent years there has been greater emphasis on the use of simulation in the acquisition process.

Since October 1995, Dr. Paul Kaminski, the Under Secretary of Defense for Acquisition and Technology, has required that the Simulation, Test and Evaluation Process (STEP), a concept of repetitive cycles of "model, test, model," be an integral part of the test and evaluation process [Ref. 7:p. iii]. This requires a decision: "which simulation should be used?" One could use an existing high-resolution model; however, according to the Defense Modeling and Simulation Office (DMSO), most present models are narrowly focused, too costly to operate, and not easily extensible. For example, Janus could be used for such an analysis; however, it does not explicitly model TUAVs. Analysts can use existing entities to perform like TUAVs, but such efforts would only be a "work around." Such limitations are inadequate for the purposes of this study. Modification of Janus to incorporate new technologies such as TUAVs and future technologies and capabilities available to TUAVs would require a tremendous amount of effort and money [Ref. 8:p. 30]. Such models may not be the best alternative for this type of analysis. The approach taken in this thesis is to use a smaller high-resolution model based on the component approach. This type of model does not require much time to develop and allows for reuse and dynamic changes that permit more in depth analysis.

C. PURPOSE.

The goal of this thesis is to evaluate the performance of TUAVs by developing simulations that will support system developers and assist decision-makers in the acquisition process. This thesis has a dual purpose. The first purpose is to evaluate measures of performance (MOP) of existing or proposed TUAV systems. The second purpose is to establish a basis to evaluate measures of effectiveness (MOE) of a TUAV system as part of sensor-shooter links within a scenario of interest. Finally, the important question to answer is:

How effective is a TUAV system in supporting a brigade's mission?

D. SCOPE.

The purpose of this thesis is not necessarily to give a specific answer to the above question but to produce a simulation tool as a proof of concept to assist decision-makers in answering important structural and operational requirement questions about TUAV systems. By manipulating input, we can conduct parametric analysis to determine possible threshold values for key technical parameters. Also, by using parameters for existing and/or future TUAV systems, this tool can be used to perform an analysis of alternatives.

This study uses discrete event simulation models where the entities are constructed using the component approach. Benefits of this methodology include the potential for scalability and reuse. Analytic (mathematical) models as well as other Monte Carlo simulations are used to assist in verifying the portion of the model that evaluates the performance of TUAV systems. Further considerations are examined and suggestions are made for continuing work on this important problem.

E. THESIS STRUCTURE.

This thesis consists of six chapters. This first chapter has been an introduction to the problem and the content of the thesis. The second chapter covers the background of the problem in order to give the reader a better understanding for the motivation of the thesis work. The third chapter focuses on the portion of the simulation that evaluates the performance of UAVs. Additionally, a discussion of verification is presented. Chapter four discusses performance of a system and analysis of alternatives. The last two chapters present recommendations and offer a conclusion.

II. BACKGROUND

...no longer is there any doubt that UAVs will play a major military role whether it be in open conflict or peacekeeping.

-Rear Admiral Barton D. Strong
Head of the Joint Projects Office for Cruise Missiles and Unmanned Aircraft

A. HISTORICAL DEVELOPMENT.

The idea of using UAVs in military operations is not new. As early as World War I UAVs, commonly referred to as "drones," were used as aerial targets and for belligerent purposes. UAVs have been used as reconnaissance assets since the 1920's and more recently during the Korean and Vietnam Wars. The Lightning Bug UAV was one of only two aircraft to fly reconnaissance missions in North Vietnam [Ref. 9:p. 3]. In 1979, the Army fielded the first major UAV acquisition, the Aquila. However, this program was canceled because of cost, delays, and technical difficulties [Ref. 10]. Military operations in Grenada, Lebanon, and Libya highlighted the need for an on-call, inexpensive reconnaissance and Battle Damage Assessment (BDA) capability for local commanders. Consequently, the Secretary of the Navy directed acquisition of UAVs for the Navy in July 1985. The Army acquired and fielded the Pioneer system in 1990. Since Pioneer's debut, it has been used in military operations ranging from the Gulf War to Peace Keeping Operations in Bosnia [Ref. 11:p. 3].

Historically, interest in UAVs has risen and fallen. In the past few years, interest has continuously increased for two reasons. The first is the heightened sensitivity to risking human life in combat. During the Cold War, the U.S. flew reconnaissance missions over the Soviet Union. In May 1960, Francis Gary Powers' U-2 spy plane was shot down [Ref. 12]. During the Cuban Missile Crisis in October 1962, Rudolph Anderson's U-2 was shot down

and crashed in the Cuban jungle [Ref. 13]. These incidents sparked national interest in the use of alternative, unmanned means of gathering intelligence. The Air Force and other national agencies then directed resources into UAV programs [Ref. 14:p. 34]. The UAV was identified as a relatively cheap alternative "when measured against the politically risky alternatives of a soldier's death or capture while conducting intelligence operations" [Ref. 5:p. 1].

The second major reason for increasing interest in UAVs is the information-age technological advances that are the foundation of Joint Vision 2010 as discussed in Chapter I. It has been said, "An unadulterated picture still tells a thousand words." The UAV can now deliver this "picture" to the warfighter because of advances in technology along with TTP. Smaller, cheaper UAV platforms and sensor packages now allow the battlefield commander the capability of achieving a near-real time picture of the battlefield. This information, processed accurately and efficiently, may allow the commander to achieve "dominant maneuver" and "precision engagements."

To attain dominant maneuver and precision engagement, information superiority must be achieved [Ref. 15]. The UAV has played a major role in acquiring information superiority in such operations as the Persian Gulf War, Task Force XXI's deployment to the National Training Center (NTC), 4th Infantry Division Advanced WarFighting Exercises (DAWE), and operations in Somalia and Bosnia. At the conclusion of the Gulf War, Lieutenant General Boomer, USMC Central Command, praised the Pioneer system as "the single most valuable intelligence collector" [Ref. 11:p. 3]. During an Advanced Warfighting Experiment (AWE) at the NTC, blue forces were equipped with TUAVs while the red forces were not. At the conclusion of the AWE, the opposing force commander was asked, "if you could take one

system away from the blue forces, what would it be? The answer was the TUAV" [Ref. 5:p. 2].

> *The tactical UAV is absolutely critical to our brigade and division commanders.... It is their confirming sensor, and the "eyes" which enable commanders to see critical portions of their battlefield and target anything they can see.*
>
> *-Lieutenant General Paul E. Menoher, Jr.*
> *Deputy Chief of Staff for Intelligence, U.S. Army*
> *5 August 1996*

UAVs will most certainly play a major role in future military operations.

The UAV systems employed previously in "real world" operations have supported higher-level units, i.e. - Corps. With the signing of the Mission Need Statement (MNS) for Close Range Reconnaissance, Surveillance and Target Acquisition (RSTA), warfighting Commanders in Chief (CINCs) have identified a need to provide lower-level tactical units with real-time responsive RSTA. On 25 February 1999, the Military Intelligence Center UAV Operations Office submitted the ORD for the "Brigade Commander's UAV." This document outlines MOPs for a UAV that will fulfill the MNS. Still, there are many unanswered questions, some of which are: "Which UAV system best suits the needs of the brigade commander?", "How many UAVs does a brigade need?", "What are the TTPs for the use of this new system?" In addition, MOEs will be identified to answer: "How effective is a system?" Many answers to these questions can be obtained through models developed as part of Simulation Based Acquisition (SBA) using STEP.

B. SBA AND STEP.

SBA is efficient integration of modeling and simulation tools and technology in the acquisition process. The goals of SBA are [Ref. 7:p. 1-2]:

- Substantially reduce time, resources, and risk associated with the acquisition process
- Increase the quality, military utility, and supportability of fielded systems while reducing total ownership costs
- Enable Integrated Product Process Development (IPPD) across the full acquisition life cycle.

STEP is the integration of modeling and simulation with test and evaluation. More specifically, STEP is an interactive process of "model-simulate-fix-test-iterate," with the results of tests feeding back into the model [Ref. 7:p. 6]. This necessitates the existence of models that can be easily modified; moreover, such models should be dynamic and reusable. A program manager should be able to use the same model by making easy modifications throughout the acquisition process. He should not have to start over from scratch to answer additional questions [Ref. 16:p. 38].

In an effort to find a model which could be used to evaluate MOPs for a UAV system, two simulations were discovered, both developed by the Institute of Defense Analyses (IDA). The first model, a discrete event simulation using Extend™ was developed in support of the Director, Operational Test and Evaluation (DOT&E). It was developed to assist in the analysis of the effective time on station (ETOS) for the **Predator** UAV [Ref. 17]. A second model, the Military Aircraft Sustainability Simulation (MASS) is an expansion of the Extend™ model and can provide analysis for a variety of platforms [Ref. 18].

There are two limitations of MASS that must be addressed to make it more robust and therefore better suited for analysis of the TUAV. Although MASS is coded in C++ and is object-oriented, it is not component-based. Hence it is difficult to incorporate new features and/or modify entities that would be essential for an analysis of a TUAV. Secondly, several assumptions are made in MASS that are unacceptable for performance analysis in this thesis. Examples are no crew-related limitations and perfect maintenance.

Developing a simulation using Java and Simkit provides a more flexible component-based simulation that will allow easier modification of features and capabilities. A brief explanation of Simkit and the code can be obtained at URL http://diana.or.nps.navy.mil/~ahbuss/OA3302W99/. Additionally, since the model was created in Java it can be executed on virtually any platform and run from the Internet. UAVSim is a simulation that extends the MASS simulation to allow for more robust performance evaluation of TUAV systems. UAVSim models Ground Control Station (GCS) and maintenance crew related limitations, maintenance prioritization, and operational tempo (OPTEMPO) requirements. It allows for non-perfect maintenance and the ability for the user to select distributions. The aforementioned were identified as "future enhancements" to the MASS model [Ref. 18]. With such an improved model, decision-makers will be better informed in the UAV acquisition process.

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III. MODEL DEVELOPMENT

A. MODEL DESCRIPTION.

The performance evaluation portion of UAVSim is a stochastic, discrete event simulation written in Java using Simkit, a discrete event simulation package. This simulation is an abstraction of the events a TUAV system encounters during a deployment. The model allows for the evaluation of a system and alternate system(s) by modifying input parameters. A stochastic simulation model, such as UAVSim, introduces uncertainly or randomness by drawing a random observation from a distribution specified by the analyst [Ref. 19:p. 32]. Randomness was introduced into the model because the "real world" system that UAVSim models also involves randomness. For example, the time between mission affecting failures, ground repair and non-mission affecting failures vary from flight to flight of the UAVs and can only be simulated using the appropriate probability distribution and estimates of that distribution's parameters. Each of these times are an integral part of the system and the effect of their randomness on the "real world" system can best be approximated by introducing randomness in the model. The measures of performance (MOP) which this thesis attempts to estimate are accordingly also random.

For the purposes of this thesis, any TUAV system is considered to be part of a UAV company. This modeling decision reflects the way these systems actually support a brigade or division. For example, in the 4th Infantry Division the TUAVs supporting the brigades and division are part of a company within the 15th Aerial Exploration Battalion. We assume the company consists of the same type of TUAV. Within the company, there is a baseline of UAVs, Ground Control Station (GCS) and maintenance section as shown in Figure 1.

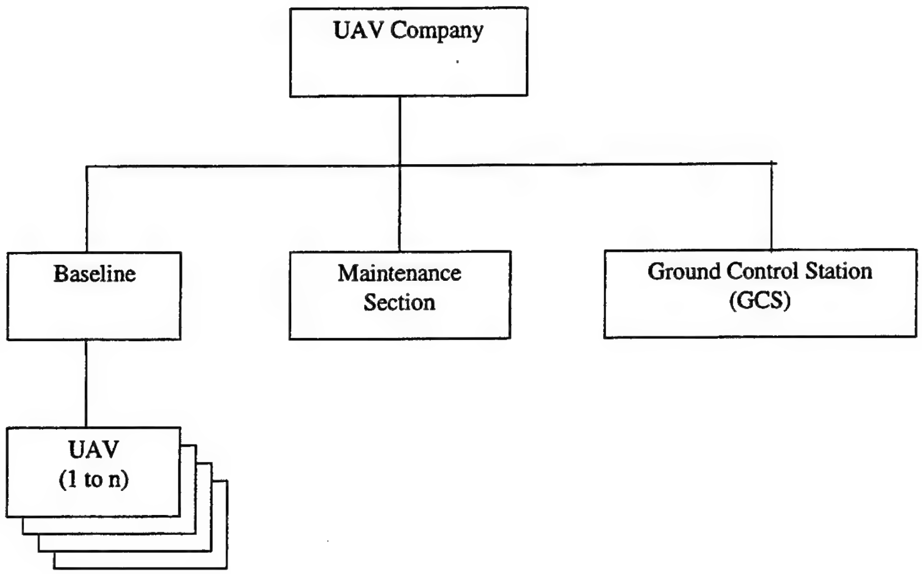

Figure 1: UAV Company Structure

1. BaseLine.

The term baseline refers to the collection of UAVs that are within the UAV company. In this study the platforms (the term platform or vehicle is a general term that refers to the TUAV) that compose the baseline are all of the same type. Since attrition is not modeled, the number of UAVs in the baseline remains constant; however, adding attrition which causes the number of UAVs in the baseline to change can easily enhance the model.

2. GCS.

The brain of the company is the GCS and controls the flight of all platforms. Within the model, it is responsible for scheduling, limiting the number of UAVs that can be flying at any given time, maintaining an "audit trail" of the actions of the company, and collecting statistics on MOPs.

3. Maintenance Team.

The company's maintenance section is responsible for servicing the platforms and sensors. This model allows for the existence of single or multiple maintenance paths that perform the same types of maintenance, routine or scheduled. Each service is based on a first-in, first-out (FIFO) queue. Also, once a platform has been serviced, it is considered "as good as new." It is assumed the UAVs are not permitted to exhibit "wear and tear."

B. MODEL EVENTS AND DESCRIPTION.

UAVSim models the different events a TUAV encounters during a deployment. Figure 2 shows these processes.

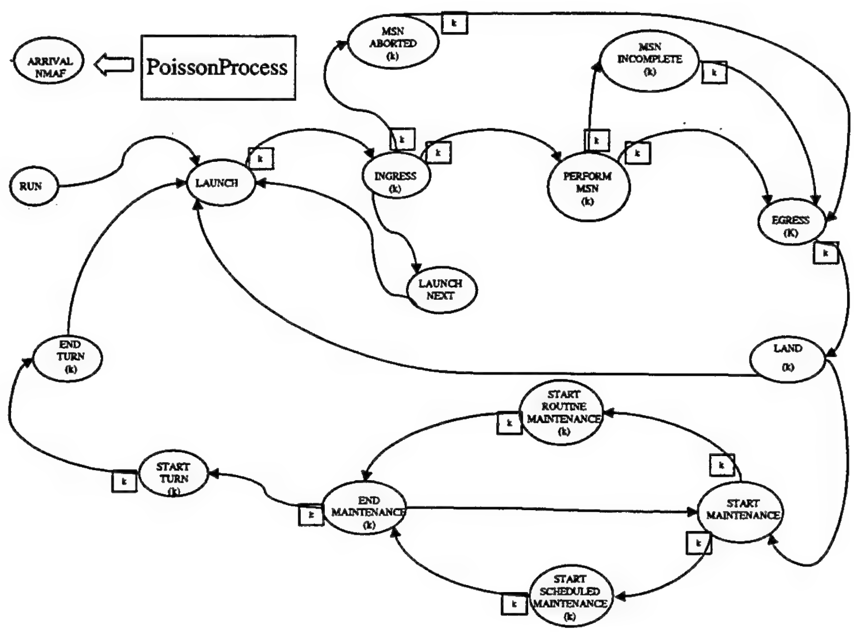

Figure 2: Event Graph of UAVSim.

A detailed discussion of event graphs and their use in simulation modeling is presented in "Modeling with Event Graphs" [Ref. 20]. The reader should not consider an event graph the same as a flow diagram.

A UAV starts by being assigned a mission, removed from the company's baseline, and launched. The UAV ingresses for a pre-planned amount of time in order to reach a specified region, the area of operation (AO). Upon arriving in the AO, the UAV observes the area for a pre-planned amount of time and then egresses. In this simulation, only one UAV is permitted to search or operate in the AO. The amount of time a UAV egresses is the same as that spent ingressing. Once the UAV lands, it proceeds to the maintenance section where the type of maintenance required is determined. If routine maintenance is to be performed, the maintenance time is exponentially distributed plus a fixed amount of time for logistics delay. If a scheduled maintenance is to be performed, the maintenance time is a pre-determined value plus the logistics delay. Only one vehicle can be serviced at a time on a given path.

During flight, the platform is susceptible to mission affecting failures (MAF) and non-MAFs. If a MAF occurs while the platform is ingressing or performing its mission, the UAV immediately egresses and proceeds to the maintenance section for servicing provided a maintenance path is available. If a path is not available, the UAV queues for maintenance. It is assumed that the distribution for all MAF repairs is independent and identically distributed (iid) exponential. The random times from take-off to the occurrence of a MAF are also considered to be iid exponential; thus UAVs always start a mission "as good as new."

Non-MAFs are the second type of failures that can occur while a UAV is flying; however, these failures do not cause the vehicle to egress. The occurrence of this type of failure is modeled as the counts of a Poisson Process. UAVSim "listens" to the component, PoissonProcess, for the occurrence of a non-MAF and increments the number of non-MAFs which have occurred. Figure 3, shows this process. The accumulation of this type of failure only increases the required maintenance time.

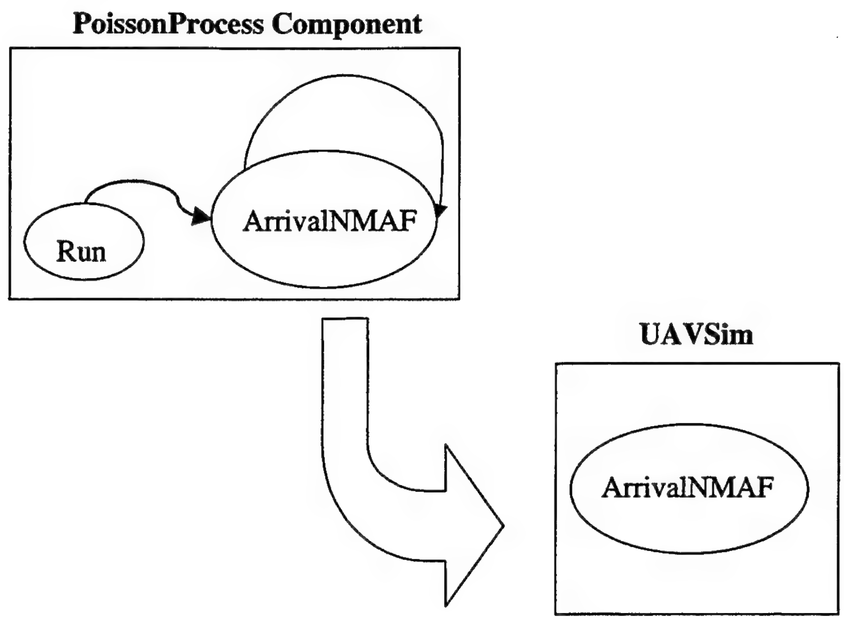

Figure 3: Occurrence of Non-MAFs Model

Similar to MAFs, the repair distribution for non-MAFs is assumed to be iid exponential. To eliminate this assumption, one could use data from operational tests and determine the distributions that are required. Due to time constraints and lack of data, this technique was not used.

After maintenance, the UAV enters the turn phase where it spends a pre-determined amount of time called "Turn Time" (TT). The purpose of the turn phase is to administratively prepare the platform for the next mission. Following completion of this phase, the UAV enters the baseline and awaits orders to perform its next mission.

Brief descriptions of the events shown in Figure 2, are presented in Table 1.

Launch	This is the first event that a UAV executes. A UAV is taken out of the baseline and immediately begins ingressing.
Ingress	The UAV flies toward the AO to perform surveillance. While the UAV is ingressing, it may have a MAF. If so, the UAV immediately aborts and egresses.
LaunchNextUAV	Once a UAV begins ingressing, the launch of the next UAV is scheduled such that as the current UAV begins egressing, the next UAV begins performing its mission. If the current UAV aborts the mission, a UAV is launched immediately given that one is available. However, if a UAV is not available, the AO is not covered until the next available UAV can arrive on station.
MissionAborted	When a UAV has a MAF during ingress, it aborts and immediately egresses. Since the platform did not travel for the full ingress time, the egress time is adjusted accordingly.
PerformMission	The UAV successfully begins coverage of the assigned region; however, it may have a MAF forcing a Mission Incomplete status.
MissionIncomplete	If a UAV has a MAF while it is providing surveillance of the AO, it immediately egresses.
Egress	The UAV is in the process of returning to its origin. Any MAF that occurs has no effect on the flight of the UAV.
Land	The UAV stops flying, enters the maintenance queue and is prepared to enter maintenance. If another UAV should have been launched earlier but could not because of limitations on the number of UAVs flying, a UAV is due to be launched. Provided there are UAVs available to be launched, a signal is sent to the "Launch" method.
StartMaintenance	Either the UAV enters routine or scheduled maintenance. If the platform has flown less than a designated amount of time, the platform enters routine maintenance. If the UAV has flown more than a designated amount of time, the platform enters scheduled maintenance. Once a platform begins this event, the number of available maintenance paths is decreased. If no maintenance paths are available, the UAV enters the maintenance queue. In this version of the model, a UAV cannot skip maintenance.
StartRoutineMaintenance	The maintenance section performs routine maintenance on the UAV.
StartScheduledMaintenance	The maintenance section performs scheduled maintenance on the UAV.
EndMaintenance	The UAV exits the maintenance queue. If there are UAVs awaiting maintenance, a signal is sent to "StartMaintenance."
StartTurn	The platform has completed maintenance and is administratively prepared for the next mission. The amount of time spent in this phase is deterministic.

EndTurn	The platform is prepared for the next mission, enters the company baseline and awaits instructions to begin the next mission. If another UAV is due to be launched, a signal is sent to the "Launch" method.
Arrival	The arrival of non-MAF is modeled as a Poisson Process. UAVSim is linked to another component, PoissonProcess that is running simultaneously. UAVSim "listens" for the arrival of non-MAFs. The number of non-MAFs that occur while a UAV is flying is recorded and used to adjust the amount of time that UAVs spend in maintenance.

Table 1: Description of Events in Version 1.0 of UAVSim

C. MODEL ASSUMPTIONS.

In the development of this model, several initial assumptions were made to decrease the complexity of the model and allow comparison between UAVSim and MASS. If the models compared are run using similar assumptions and input parameters, each model should return similar results. It should be noted that some of these assumptions will be relaxed when the model is expanded to handle more complex issues appropriate for modeling TUAVs. The initial assumptions that were made are presented in Table 2.

1. No Attrition or Loss of Platforms	No attrition or loss of platforms is modeled. Only MAF cause a platform not to perform its mission.
2. No Weather-Related Effects	Bad weather (heavy rain, snow) does not affect the performance of the UAV.
3. No Ground aborts	No ground aborts occur. Once a UAV is dedicated to ingress, it will ingress. No MAFs occur before launch.
4. Distributions of MAF and Repair Times	All classifications of MAF (human, mechanical, etc) are aggregated into the general classification of MAFs. The times between MAFs are modeled as iid observations from an exponential distribution. Additionally, repair times are modeled as iid observations from an exponential distribution. These distributions remain constant throughout the deployment.
5. No Wear and Tear	At the conclusion of maintenance actions, UAVs are 100% mission capable; platforms receive perfect maintenance and do not exhibit "wear and tear."
6. No Function Checks	After completion of the maintenance phase, no function checks are performed.
7. No Crew-Related Limitations	Crew-related limitations such as numbers of pilots/payload operators, flight hours that pilots/payload operator can fly, numbers of mechanics or the number of hours that mechanics can work are limiting factors. None of these limitations are modeled initially.

Table 2: Initial Model Assumptions

D. MODEL INPUTS.

The input parameters for UAVSim are very similar to those used in MASS. This similarity further facilitates the development of a model like MASS. The initial inputs for the model and a brief description are given in Table 3.

Number of UAVs	The number of UAVs in a baseline.
Number of Maintenance Paths	The number of paths available to service platforms. Maintenance paths are equivalent to servers.
Maximum Number of UAVs in Flight	The GCS can only control a specified number of UAVs at a given time.
Ingress Time (hours)	The length of flight from the launch and recovery site to the region to be observed.
Egress Time (hours)	The amount of time the platform requires to reach the launch and recovery site from the position where it begins egressing.
Scheduled Time on Station (hours)	The pre-planned amount of time a platform is scheduled to spend in the AO.
Number of Deployments	The number of replications of the simulation. One run may consist of several replications or deployments. This also known as the sample size.
Platform Turn Time (hours)	The time required to prepare a UAV for a subsequent launch. TT is a constant.
Logistics Delay Time (hours)	The length of time required to obtain parts, for a piece of equipment to become available, etc. This time is added to whatever time is required for maintenance. This is a constant.
Mean Time for Ground Repair (hours)	The expected time for the maintenance section to service a platform.
Time to Complete Scheduled Maintenance (hours)	The time associated with the maintenance section completing a scheduled maintenance for a UAV. This time is assumed to be constant.

Time to Repair Each Non-MAF (hours)	The time required by the maintenance section to repair each non-MAF. This value is assumed to be a constant.
Flight Time Between Scheduled Maintenance Actions (hours)	The amount of time the platform may fly before a scheduled maintenance. This time is assumed to be constant.
Mean Time Between Platform MAF (hours)	The expected time between occurrences of MAFs. In this version of the model, the time between platform MAFs is exponential.
Length of Deployment (days)	The length of a deployment or replication of the model.
Mean Time Between Non-MAF (hours)	The expected time between occurrences of non-MAFs. In this version of the model, the time between platform MAFs is exponential.
z-Value	This is the z-value from the standard normal distribution. The number specified is used to determine the confidence interval for MOPs.

Table 3: Description of Model Inputs

E. MODEL OUTPUTS.

The initial UAVSim model returns MOPs identical to those returned by the MASS model. This allows easy comparison of results and also facilitates comparison of the models to determine if UAVSim is operating as it should. The initial MOPs generated by UAVSim are presented in Table 4.

Effective Time On Station (ETOS)	The mean percentage of time that the AO is covered by at least one UAV.
Time Non-Mission Capable (NMC)	This is the mean time platforms are non-mission capable given that a MAF occurs. This time is measured from the moment a MAF occurs until it has completed maintenance.
Sortie Generation Rate (sorties per time period)	The average number of launches during a deployment.
Mean Wait Time in Maintenance Queue	The average amount of time that UAVs spend waiting for maintenance given that there is more than one UAV in the baseline.

Table 4: Description of Model Outputs

Both MASS and UAVSim compute confidence intervals for each of the MOPs. As part of the input parameters, the user specifies the number of deployments, the sample size, and a confidence level by entering the appropriate value for a standard normal random variable, referred to as the "z-value." Each of the MOPs is the mean from several observations or in this case, deployments. By using the Central Limit Theorem (CLT), if the number of replications (deployments) of the simulation is sufficiently large, the MOP has approximately a normal distribution [Ref. 21:p. 232]. Using point estimators for the mean and standard deviations, UAVSim calculates and presents a confidence interval corresponding to the "z-value" the user specified.

F. VERIFICATION OF MOP NORMALITY ASSUMPTION.

As mentioned previously, the values for the MOPs and the Bonferroni intervals were computed using the assumption that each observation of the MOP was iid normal. In order to verify this assumption, diagnostic plots and goodness of fit tests were used. The Chi-Square Test for Goodness of Fit and the Kolmogorov-Smirnov Test in the statistical analysis package S-Plus 4.5 were used.

1. Diagnostic Plot.

One run of UAVSim in which the number of deployments was set to thirty was completed. The ETOS for each deployment was captured and imported into S-Plus. A "qqnorm" plot of the data is shown in Figure 4. Each point in the figure represents the average of the count of total hours UAVs provided coverage divided by the total count of hours that coverage should have been provided.

The plot appears to indicate that the data is close to normal; however, more robust analysis and determination can be completed with the goodness of fit tests. The first test applied was the Kolmogorov-Smirnov composite test.

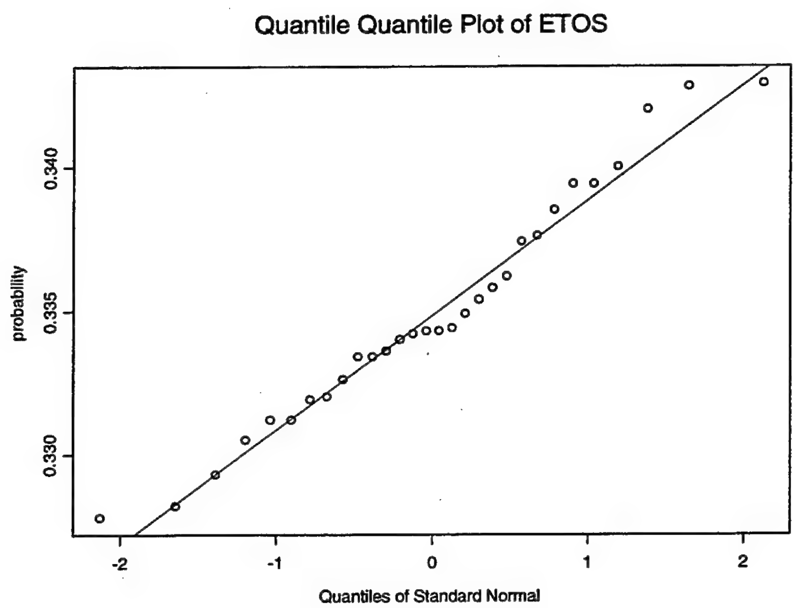

Figure 4: Quantile-Quantile Plot of ETOS

2. Goodness of Fit Tests.

The composite tests were used because it is hypothesized that the data comes from a normal distribution but the parameters, μ and σ, are estimated and not known. The null and alternate hypotheses are:

H_o: The true cdf equals the normal distribution for all sample points.

H_a: The true cdf does not equal the normal distribution for at least one sample point.

The values for μ and σ were estimated and an exploratory plot of the empirical and hypothesized distribution was conducted, Figure B-1 at APPENDIX B. The plot indicates that the distributions appear to be the same. Next, applying the Kolmogorov-Smirnov test resulted in a p-value of 0.72. Since a value of 0.05 was used for α, the null hypothesis was not rejected. Similarly, the p-value from the Chi-square Goodness of Fit Test was 0.68 and the null hypothesis could not be rejected. Given the test results and efforts, it is assumed that the observations of the MOP are iid normal.

This will allow us to safely use confidence intervals and other inference techniques based on the normal distribution.

3. Independent Observations.

The value of ETOS was computed for each run of the simulation with iid observations from distributions within the model. Thus the resulting value of ETOS conditioned on the parameter values for a particular run is independent of the other runs.

G. VERIFICATION OF THE MODEL.

In the development of a model, important questions are: "Does this model do what it is supposed to do?" or "Has this model been verified?" Verification is "the process of determining that a model implementation accurately represents the developer's conceptual

description and specifications" [Ref. 22:p. I-3]. Verification of UAVSim was conducted using two independent methods. The first used an analytical model developed by Gaver, Jacobs and Stoneman [Ref. 22:p. 3]. The second method used a similar simulation, the MASS model. Two cases were explored in the verification process: single platform/single maintenance path (Case I) and multiple platforms/single maintenance path (Case II). It should be noted that both models were used to verify UAVSim in Case I; however, only the MASS model was used in Case II. The analytical model could not be used in Case II because of the complex scheduling requirement when more than one UAV is available. For each case all models use the same assumptions and processes.

1. Case I Comparison.

This analytical model assumes that the time to a MAF is exponentially distributed with rate λ. Upon returning to the launch and recovery site, the platform is serviced by the maintenance section where the time to repair is exponentially distributed with rate μ. The formulas to find the long run proportion of time on station (ETOS) for the analytical model are [Ref. 23:p. 3]:

$$\pi = \frac{e^{-\lambda T}\frac{1}{\lambda}[1-e^{-\lambda S}]}{\frac{1}{\mu}[1-e^{-\lambda(2T+S)}]+\frac{2}{\lambda}[1-e^{-\lambda T}]+e^{-\lambda T}\frac{1}{\lambda}[1-e^{-\lambda S}]+E[D]} \qquad \text{Equation 1}$$

where T = Ingress/Egress Time
S = On Station Time
E[D] = Expected additional time the UAV is not flying

$$E[D] = \alpha_U E[B]\frac{1}{\beta_U} + \alpha_s E[B]\frac{1}{\beta_S} + \frac{1}{\beta_A} \qquad \text{Equation 2}$$

where $1/\alpha_U$ = mean time between non-mission affecting failures
$E[B]$ = expected time from launch until landing
$1/\beta_U$ = time to complete each non-mission affecting failure
$1/\alpha_S$ = time to complete scheduled maintenance actions
$1/\beta_S$ = time between scheduled maintenance actions
$1/\beta_A$ = logistics delay time + turn time

$$E[B] = \frac{2}{\lambda}\left[1 - e^{-\lambda T}\right] + e^{-\lambda T}\frac{1}{\lambda}\left[1 - e^{-\lambda S}\right] \qquad \text{Equation 3}$$

where λ, T, and S are as defined above

The next step in the comparison was to enter identical parameters into the UAVSim, MASS and analytical models. The input parameters for the three models were those listed in Table 5. Also, Table 6 shows a mapping of UAVSim for the analytical model.

```
Number of platforms: 1
Number of maintenance paths: 1
Maximum number of platforms in flight :2
Length of deployment (hours): 2160.0
Number of simulated deployments: 50
Ingress time (hours): 1.0
Egress time (hours): 1.0
Scheduled on station time (hours): 18.0
Platform turn time (hours): 0.0
Logistics delay (hours): 0.5
Mean time for ground repairs (hours): 1.9
Time to complete scheduled maintenance (hours): 7.0
Time to complete each non-mission affecting failure (hours): 1.9
Flight time between scheduled maintenance actions (hours): 50.0
Mean time between mission affecting failures (hours): 25.0
Mean time between non-mission affecting failures (hours): 5.0
Endurance is limited to 20 hours (ingress + egress + tSOS ≤ endurance)
```

Table 5: Model Inputs for Case I

$T = 1.0$ (ingress/egress) $S = 18.0$ (scheduled time on station) $1/\lambda = 25$ (mean time between mission affecting failures) $1/\mu = 1/1.9$ (mean time for ground repairs) $1/\alpha_U = 5.0$ (mean time between non-mission affecting failures) $1/\beta_U = 1.9$ (time to complete each non-mission affecting failure) $1/\alpha_S = 7.0$ (time to complete scheduled maintenance actions) $1/\beta_S = 50.0$ (time between scheduled maintenance actions) $1/\beta_A = 0.5$ (logistics delay time + turn time)

Table 6: Example Mapping of UAVSim Inputs.
This mapping is for the very first calculation in Table 7.

The parameters in bold in Table 5 were modified for each run. T was the ingress/egress time and tSOS was the scheduled time on station. The sum of the ingress/egress times and scheduled time on station was limited to 20 hours. For example, when T = 1, the ingress and egress time is set to one hour. Since the TUAV only has twenty total hours endurance, there are only eighteen remaining hours for on station time.

The results of the single platform comparison are shown in Table 7 and Figure 5. Note that for each run, a different ingress/egress and scheduled time on station was used. Also, each run encompassed fifty deployments, hence the sample size was fifty. The length of each deployment was 2,150 hours which is the same length used for analysis performed with MASS.

T (hrs)	tSOS (hrs)	Analytic ETOS	MASS ETOS (95% Bonferroni Interval)	UAVSim ETOS (95% Bonferroni Interval)
1	18.0	0.5298	0.5177 - 0.5355	0.5060 - 0.5418
2	16.0	0.4507	0.4368 - 0.4532	0.4331 - 0.4680
3	14.0	0.3802	0.3671 - 0.3875	0.3694 - 0.3988
4	12.0	0.3164	0.3093 - 0.3312	0.3070 - 0.3357
5	10.0	0.2576	0.2502 - 0.2691	0.2456 - 0.2790
6	8.0	0.2027	0.2008 - 0.2164	0.1937 - 0.2199

Table 7: Case I Comparison Data

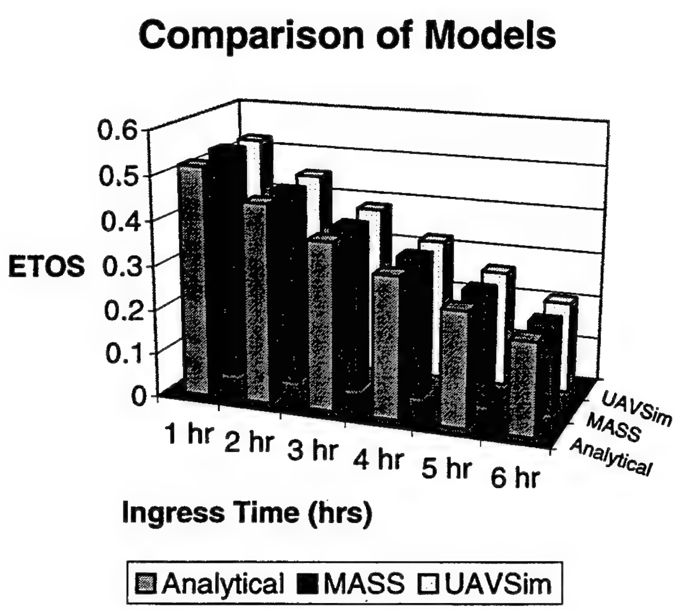

Figure 5: Case I Comparison of Models

The values for ETOS from the analytical model and MASS and UAVSim simulations appear to agree well. Specifically, the values from the analytical model are within the Bonferroni confidence intervals generated by UAVSim. Also, each of the confidence intervals from the two simulations overlap for all 6 cases which indicates that the simulations do not have results that are significantly different.

2. Case II Comparison.

A comparison of UAVSim and MASS was conducted for the case of multiple UAVs and a single maintenance path. The inputs for both models are listed below. Note that the number of UAVs was set at four and the number of maintenance paths was limited to one. In this situation, there was the possibility for congestion or wait time when UAVs must be serviced. The input data for this comparison is shown in Table 8.

```
Number of platforms: 4
Number of maintenance paths: 1
Maximum number of platforms in flight :2
Length of deployment (hours): 2160.0
Number of simulated deployments: 50
Ingress time (hours): 1.0
Egress time (hours): 1.0
Scheduled on station time (hours): 18.0
Platform turn time (hours): 0.0
Logistics delay (hours): 0.5
Mean time for ground repairs (hours): 1.9
Time to complete scheduled maintenance (hours): 7.0
Time to complete each non-mission affecting failure (hours): 1.9
Flight time between scheduled maintenance actions (hours): 50,000.0
Mean time between mission affecting failures (hours): 25.0
Mean time between non-mission affecting failures (hours): 50,000.0
Endurance is limited to 20 hours (ingress + egress + tSOS ≤ endurance)
```

Table 8: Model Inputs for Case II

The results of the MASS and UAVSim simulations are presented in Table 9. Note that for each run, a different ingress/egress and scheduled time on station was used. Also, each run consisted of fifty deployments, as a result the sample size was fifty. The length of each deployment was 2,150 hours which is the same length used for analysis purposes with MASS.

T (hrs)	tSOS (hrs)	MASS ETOS (95% Bonferroni Interval)	UAVSim ETOS (95% Bonferroni Interval)
1	18.0	0.9516 - 0.9617	0.9673 - 0.9943
2	16.0	0.8939 - 0.9232	0.9141 - 0.9717
3	14.0	0.8247 - 0.8653	0.8424 - 0.9067
4	12.0	0.7637 - 0.7957	0.7337 - 0.8109
5	10.0	0.6489 - 0.6887	0.5932 - 0.6634
6	8.0	0.5184 - 0.5539	0.4844 - 0.5418

Table 9: Case II Comparison Data

The Bonferroni confidence intervals from both the MASS and UAVSim models are relatively close and overlap in all but the first case. As in Case I, it appears that there is no significant difference in the models. The simulations are yielding similar results.

Thus far, it has been shown by comparison to two independent methods, the analytical model and the MASS simulation, that there does not appear to be a significant difference in the resulting MOPs in comparison with UAVSim. Every effort has been made to establish the same assumptions, enter identical input parameters, extract the same MOPs, and test for statistical differences in the MOPs. Having performed these tasks, and given their results, I conclude that UAVSim is performing as it should. It is providing data close enough to that of these previously existing models so that further study can be performed.

H. EXPANSION OF THE MODEL.

As discussed in Chapter II, the present version of MASS must be expanded for evaluation of tactical UAVs. Specifically, sensor package failures, enhanced maintenance system, maintenance prioritization, non-perfect maintenance, GCS and maintenance crew-related limitations, ability to specify distributions and the ability to perform non-continuous operations must be added. A listing of each of the features that were added to UAVSim is presented in Table 10.

Sensor Package Failures	The user can specify the distribution and parameters for the sensor package failure time. All sensor package failures are treated as MAFs and as such cause the UAV to immediately egress.
Enhanced Maintenance System	The maintenance portion of the model was expanded to better ascertain the type of service required and appropriate maintenance repair time.
Maintenance Prioritization	The user has the option to select priority maintenance. If priority maintenance is chosen, maintenance is performed based on the required maintenance time. Lower required maintenance times have priority.
Non-Perfect Maintenance	When UAVs are serviced, they are not "as good as new."
GCS Crew Limitations	The number of pilot/payload operator teams that are available can limit UAV operation. Flight hour constraints are listed in U.S. Army Regulation 95-XX [Ref. 24:p. 23].
Maintenance Crew Limitations	The number of maintenance personnel available for service can limit the model. Also, the maximum number of hours that a team can work per day can restrict performance.
Specification of Distributions	The operator can specify the distribution and the corresponding parameters for: • Time to Platform MAF • Time to Sensor MAF • Repair Time for Platform MAF • Repair Time for Sensor MAF • Logistics Delay Time
Non-Continuous Operations	The user can select whether or not OPTEMPO and Surge OPTEMPO constraints are active. OPTEMPO requirements are requirements for the UAV Company to achieve a specified number of coverage hours per day. Surge OPTEMPO requirements are requirements to achieve a specified number of coverage hours per day but only for a specified number of days after which the required number of coverage hours for one day is less.

Table 10: Listing of Expanded Model Features

I. EXPANDED MODEL EVENTS AND DESCRIPTION.

The expansion of UAVSim was accomplished by adding additional methods to the existing simulation and by developing other components that UAVSim could communicate with while running. The addition of sensor package failures, maintenance prioritization, non-

perfect maintenance and specification of distributions was accomplished by adding methods to the existing model. However, GCS and maintenance crew-related limitations, and non-continuous operations were added through linking the existing model to new components. Figure 6 shows the structure of the expanded model.

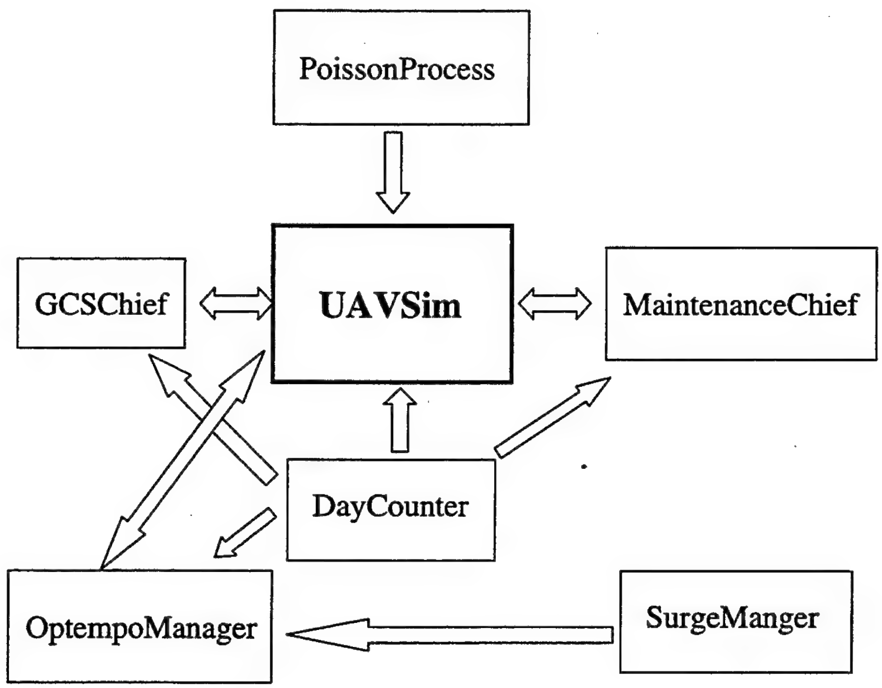

Figure 6: Structure of Expanded Model

A description of each of the additions to the model follows:

1. Maintenance Crew-Related Limitations.

Maintenance crew-related limitations were modeled using the MaintenanceChief component. An event graph of this model is shown in Figure 7. The input for this component is the maximum number of hours that the maintenance team can work in a given day. When the user specifies that maintenance constraints are to be active, UAVSim and the MaintenanceChief communicate when a UAV requires maintenance. UAVSim sends the

UAV requiring maintenance to the MaintenanceChief that compares the required maintenance time to the available maintenance time (time remaining that the mechanic team can work). If the available time is greater than or equal to the required time, the UAV enters the maintenance path and is serviced. However, if the available time is less than the required maintenance time, the UAV enters the maintenance queue. If there are other UAVs in the maintenance queue, they are checked in the order in which they would be serviced and maintenance is performed if time is available. All or none of maintenance is performed; partial maintenance is not allowed. The amount of available maintenance time is only decreased when a UAV is being serviced. Otherwise, the maintenance team is idle and waiting for a UAV to service. The maintenance team is on call 24 hours a day and can work intermittently, but less than or equal to a fixed number of hours. At the conclusion of the day, the available maintenance time is reset; remaining time cannot be carried over to the next day. The model allows only the existence of one maintenance team.

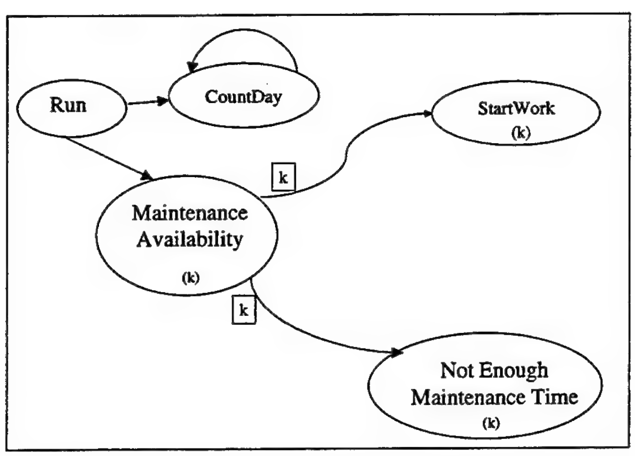

Figure 7: MaintenanceChief Event Graph

2. GCS Crew-Related Limitations.

GCS crew-related limitations were modeled using the GCSChief component. An event graph of this model is shown in Figure 8. The input for this component is the number of GCS teams (pilot and payload operator) and the policy that governs the maximum number of hours per day that a GCS team can control UAVs. The policy which governs the number of hours per day that a GCS team can fly is outlined in AR 95-XX [Ref. 24:p. 23].

If the user specifies that GCS constraints are to be active, UAVSim and GCSChief communicate when a UAV is required to launch. UAVSim sends the UAV requiring launch to the GCSChief which compares the required flight time to the available flight time (time remaining that the GCS teams can fly). If the available time is greater than or equal to the required time, the UAV is launched. However, if the available flight time is less than the required time, the UAV remains in the baseline. If there are other UAVs in the baseline, they are checked and launched if crew time is available. The team is on call 24 hours a day and can

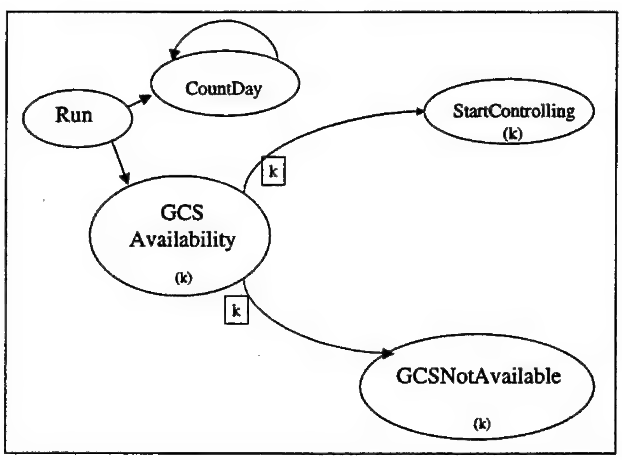

Figure 8: GCSChief Event Graph

work intermittently, but less than or equal to a fixed number of hours. The available flying time is only decreased when a UAV is flying; otherwise, the crew is idle waiting to fly a UAV. At the conclusion of the day, the available flight time is reset according to the flight hour policy that is modified based on the number of days that the UAV company has been operating. Available time cannot be carried over to the next day. The flight policy, which was used in this study, is shown in Table 11. It should be noted that UAVs, which fly during the same time or portion of the same time, share GCS flying time. The current version of the model only allows the existence of one GCS team.

Number of Days of Operation	Max Flight Hours
1-7	14 hrs
8-11	8 hrs
12-16	5.87 hrs

Table 11: Flight Hour Policy

3. Non-Continuous Operations.

There are two types of non-continuous coverage operations and associated requirements: OPTEMPO requirements and surge requirements. OPTEMPO requirements are the number of hours that a commander desires to have coverage of an AO everyday. Surge requirements are a higher number of coverage hours that a commander requires for an AO. At the end of a specified period, the increased number of required coverage hours is decreased. For example, an OPTEMPO requirement may be that a commander wants to have twelve hours of continuous coverage every day. On the other hand, a surge requirement may be the commander's desire to have eighteen hours of coverage per day for three days and then

eight hours of coverage on the following day. The intent of the limited number of hours of operation on the following day is to allow the UAV company to recover.

The OptempoManager and SurgeManager components manage non-continuous coverage requirements. Event graphs that show these models are in Figure 9 and Figure 10. When the user specifies that OPTEMPO constraints are active, UAVSim and OptempoManager communicate. However, when the user specifies that surge constraints are to be active, UAVSim, OptempoManager and SurgeManager interact. UAVSim and both components communicate when a UAV performs its mission.

The OptempoManager uses the information contained in the GCS to determine whether OPTEMPO constraints or OPTEMPO constraints as well as surge constraints are active. When only OPTEMPO constraints are active, the OptempoManager determines whether or not the required number of coverage hours has been achieved. If so, no additional UAVs are launched. Once the required coverage time has been achieved, the OptempoManager alerts UAVSim to egress all UAVs. When all UAVs have landed and completed maintenance, UAVSim determines the length of the company's down period. The down period is the remaining number of hours in the current day the company will be inactive. At the beginning of the next day, the company begins operations once again.

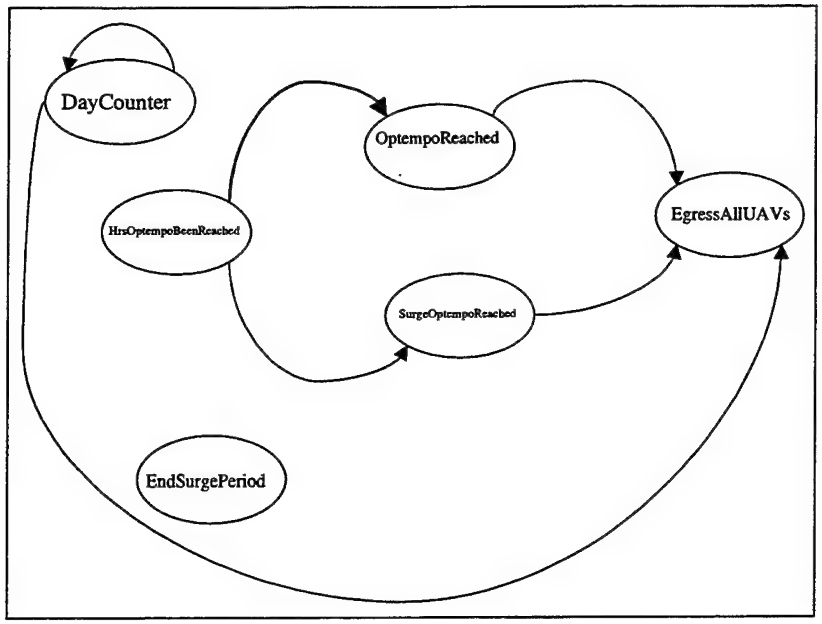

Figure 9: OptempoManager Event Graph

When both OPTEMPO and surge constraints are active, the OptempoManager uses the GCS's information as well as information from the SurgeManager. Until SurgeManager notifies OptempoManager that the surge period has ended, operations are the same as previously described when there are no surge requirements. When OptempoManager is notified that the surge period has ended, the number of required coverage hours becomes the required number of coverage hours for the period following surge operations. Upon achieving this requirement, the OptempoManager notifies UAVSim to egress all UAVs just as previously discussed. The number of hours required for the UAV company to achieve the limited coverage is recorded and when all UAVs have completed maintenance, the company's down time is also recorded.

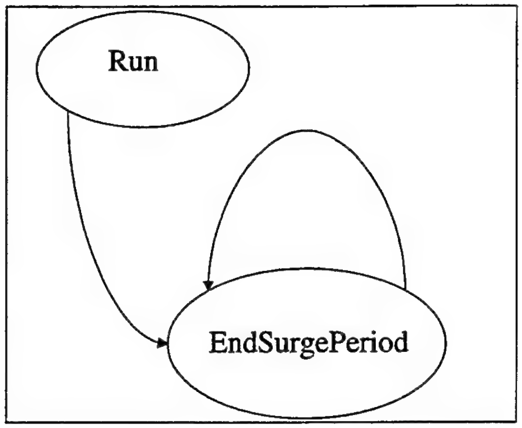

Figure 10: SurgeManager Event Graph

4. Sensor Package Failures.

The need for sensor package failures was added because of specifications listed in the ORD. These failures are considered to be MAFs. The time at which a sensor package failure occurs is determined by drawing a random number from the sensor package failure distribution. This time starts at launch; a MAF can only occur during flight. Given that both platform and sensor package failures are MAFs, the point at which a UAV becomes non-mission capable is determined by finding the minimum of a UAV's platform MAF time and sensor package failure time. If the cause of the UAV's MAF was the sensor package failing, the length of maintenance time is drawn from the Repair Sensor MAF distribution.

5. Maintenance Prioritization.

When maintenance prioritization is used, UAVs enter a priority queue after landing. The priority of this queue is determined by required maintenance times where lower maintenance times have higher priority. Prioritization is not preemptive.

6. Enhanced Maintenance System.

The maintenance portion of the model was expanded so that the appropriate type of maintenance and the corresponding maintenance time could be assigned. Two types of maintenance are modeled: corrective and preventive. Corrective maintenance consists of all maintenance actions as a result of a MAF plus any scheduled maintenance that is due. Preventive maintenance is all maintenance necessary to sustain the UAV. The goal of preventive maintenance is to retain the UAV at a certain level of performance [Ref. 25:p. 48].

When each UAV enters the maintenance phase, a determination of whether a MAF occurred is made. If a MAF occurred, the UAV enters corrective maintenance. Otherwise, the UAV enters preventive maintenance. When corrective maintenance must be performed, a determination of whether or not a service is due and the cause of the MAF is made. If a service is due, the required maintenance time is the sum of the scheduled service time, logistics delay time, non-MAF repair time, and the time to repair the MAF. Else, the required maintenance time is the same sum less the scheduled service time. If the UAV is to undergo preventive maintenance, the requirement for a service is also determined. Should the UAV require a service, the maintenance time is the scheduled maintenance time, plus the logistics delay and non-MAF times. Otherwise, the maintenance time is the sum of the preventive maintenance time, logistics delay time and non-MAF repair time. Figure 11 shows this maintenance flow.

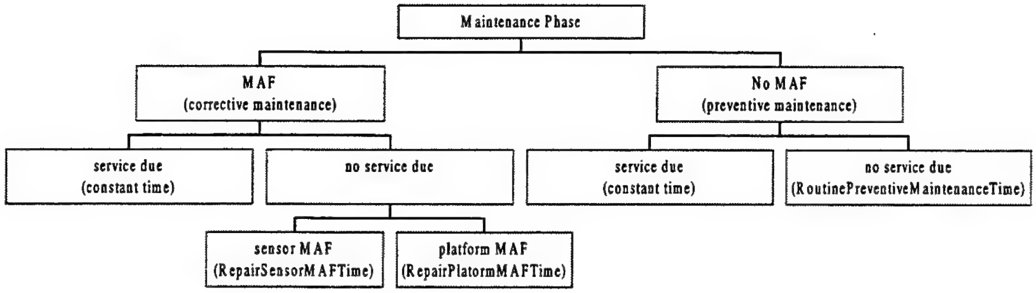

Figure 11: Enhanced Maintenance System Flow

7. Non-Perfect Maintenance.

Imperfect maintenance was modeled by allowing the UAV to "remember" after how many flight hours it would experience a MAF. This is an option in the model. Each time a UAV enters preventive maintenance, under this option the flight time is subtracted from the time to occurrence of the next scheduled MAF. Thus, the UAV would continue to fly until it had the assigned MAF. This negates the "good as new" assumption.

8. Specification of Distributions.

The analyst has the option to specify the distribution and corresponding parameters for each of the distributions used in the model. This feature was added so analysts could perform analysis without being restricted to the exponential distribution, as it may not always be appropriate.

J. EXPANDED MODEL ASSUMPTIONS.

Given the added features of the model, not all of the original assumptions are necessary. Referring to Table 2, original assumptions 5 and 7 are no longer needed. The initial assumption of perfect maintenance can be optionally eliminated. Crew-related limitations are added with the addition of the GCSChief and MaintenanceChief components.

Now the number of personnel available to work and the number of hours that they can work are limiting factors.

K. EXPANDED MODEL INPUTS.

The expanded version of UAVSim has the same inputs as previously discussed with the addition of the new inputs listed in Table 12. The inputs which were added are those required to make the model more robust and allow for analysis of requirements specific to the TUAV. Specifically, TUAV systems typically do not have the endurance, number of platforms, or number of personnel to perform extended continuous operations.

Prioritize Maintenance	The user can specify whether or not a priority queue is used when determining which UAV is serviced next.
Wear and Tear	Allows the user to specify whether or not UAVs are "as good as new" once they are serviced.
Optempo (hours)	The requirement for a UAV to achieve a specified number of coverage hours per day.
Optempo Constraints	Allows the user to indicate whether or not there is a requirement for non-continuous operations.
Surge Constraints	Allows the user to indicate whether there is a requirement for the company to "surge" for a specified length of time.
Surge Period (days)	The length of time that the UAV company will perform surge operations.
Surge Optempo (hours)	The limited amount of time that a UAV company must provide coverage before returning to optempo requirements.
Maintenance Constraints	Indicates if UAV company operations will be limited by maintenance crew-related limitations.
Maximum Maintenance Work Hours	The maximum number of hours that the maintenance team can work per day.
GCS Constraints	Indicates if the UAV company operations will be limited by GCS crew-related limitations.

Distributions and Parameters	The following times require distributions and the corresponding parameters: • Time to Platform MAF • Time to Sensor MAF • Repair Time for Sensor MAF • Repair Time for Platform MAF • Preventive Maintenance Time • Logistics Delay Time A brief description of each of these random times is given in Table 14. There are several distributions available in UAVSim. A listing of the available distributions and the required parameters are listed in Table 15. Because of the design of UAVSim, the analyst can also code and add other distributions as well. For example, for the purposes of this thesis, the Weibull distribution was coded and added to UAVSim. The time to a non-MAF is always modeled as iid exponential and thus only requires a mean time between non-MAFs.
Length of Warm Up Period	The length of time required for the model to reach steady-state.
Relative Precision	The relative precision desired. The sample size for each run of the simulation was determined using relative precision. This concept is to make replications of the simulation until the half-length of the confidence interval divided by the mean value of the MOP is less than or equal to the desired relative error [Ref 26:p. 537].

Table 12: Expanded Model Inputs

Each of the random times is defined in the following table. The observations for each of these times are drawn from distributions that the analyst selects.

Time to Platform MAF	The time to the occurrence of a platform related MAF.
Time to Sensor MAF	The time to the occurrence of a sensor package related MAF.
Repair Time for Sensor MAF	The corrective maintenance time required to repair all deficiencies caused by a sensor MAF.
Repair Time for Platform MAF	The corrective maintenance time required to repair all deficiencies caused by a platform MAF.
Preventive Maintenance Time	The preventive maintenance time required to sustain the performance of the UAV. The mean of these observations is the mean preventive maintenance time (Mpt) or mean time to repair (MTTR).
Logistics Delay Time (LDT)	The maintenance downtime as a result of waiting for spare parts, waiting for availability of equipment, etc.

Table 13: Description of Each Random Time

The following table lists the distributions that are available in UAVSim and the required parameters for each.

Distribution	Parameters	pdf f(x)
Weibull	α - shape parameter β - scale parameter	$f(x:\alpha,\beta)=\frac{\alpha}{\beta^{\alpha}}x^{\alpha-1}e^{-(x/\beta)^{\alpha}},x\geq 0$
Exponential	λ - rate	$f(x;\lambda)=\lambda e^{-\lambda x},x\geq 0$
Beta	α - shape parameter A - optimistic value β - scale parameter B - pessimistic value	$f(x;\alpha,\beta,A,B)=\frac{1}{B-A}\times\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\times\left(\frac{x-A}{B-A}\right)^{\alpha-1}\times\left(\frac{B-x}{B-A}\right)^{\beta-1},A\leq x\leq B$
Gamma	α - shape parameter β - scale parameter	$f(x;\alpha,\beta,)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}e^{x/\beta},x\geq 0$
Normal	μ - mean σ - standard deviation	$f(x;\mu,\sigma)=\frac{1}{\sqrt{2\pi\sigma}}e^{-[x-\mu]^2/(2\sigma^2)},-\infty<x<\infty$
Lognormal	μ - mean of ln(X) σ - standard deviation of ln(X)	$f(x;\mu,\sigma)=\frac{1}{\sqrt{2\pi\sigma x}}e^{-[\ln(x)-\mu]^2/(2\sigma^2)},x\geq 0$

Table 14: Distributions Available in UAVSim

The exponential, beta, gamma, and normal distributions are already implemented in Simkit. However, the Weibull and lognormal distributions are not in Simkit and had to be coded by the author. Refer to APPENDIX C for an explanation of the algorithms used to implement these distributions as well as verification of their results.

L. EXPANDED MODEL OUTPUTS.

The expanded version of UAVSim requires additional MOPs for analysis. Some of the previous MOPs from the MASS model and first version of UAVSim are not appropriate for analysis of TUAVs. For example, when TUAVs are performing non-continuous operations, ETOS is not a suitable MOP. A more fitting MOP is the expected number of hours required to achieve the commander's requirement for coverage of the AO. For example, if the commander specifies that he wishes to have twelve hours of continuous coverage and it takes an average of thirteen hours to achieve that requirement, then thirteen hours is the

expected number of hours required to achieve the requirement. The additional MOPs generated by the model are listed in Table 15.

Also, an example and explanation of the output files generated by UAVSim is presented in APPENDIX A.

Percent Days OPTEMPO Achieved	The percentage of days that the UAV company is able to achieve the required hours of coverage.
Hours to Achieve OPTEMPO	Given that the UAV company is able to achieve the required OPTEMPO, this is the average amount of time that was required for the UAV company to meet the requirement.
Company Down Time	Given that a UAV company achieved the required OPTEMPO, and all of the UAVs have completed maintenance on the same day that the OPTEMPO requirement was met, down time is the remaining hours of the day in which the company does not fly nor service UAVs.
Percent Days Surge OPTEMPO Achieved	The percentage of days in which the company is able to achieve the specified limited coverage requirement following a surge period.
Time to Achieve Surge OPTEMPO	The number of hours necessary for the company to achieve the limited coverage requirement following a surge period.
Company Surge Down Time	Once the company achieves the limited coverage requirement and all UAVs have been serviced, down time is the remaining part of the day in which the company does not fly UAVs nor perform maintenance.
Mean Number of Sorties	The mean number of sorties flown during a deployment.
Sortie Generation Rate (sorties/day)	The number of sorties flown per day.
Mean Wait Time in Queue	The mean time UAVs spend in the maintenance queue prior to being serviced.
Mean NMC Time	The average amount of time that a UAV is non-mission capable prior to being serviced.
Scheduled Service Ratio	Percentage of time a UAV is required to have a scheduled service.

Table 15: Expanded Model Outputs

Given the additional analytic capabilities provided by this version of UAVSim, it is now possible to explore the performance of TUAV systems by varying the input parameters. Additionally, the analyst can gain ideas about the sensitivity of TUAV performance with respect to changes in input parameters. These explorations are the focus of Chapter IV.

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IV. ANALYSIS AND RESULTS.

A. GENERAL.

As mentioned in Chapter III, UAVSim involves numerous stochastic processes. Such processes can exhibit two types of behavior: transient or steady-state. Transient behavior is indicative of early or erratic operations during which the observations are more biased toward initial conditions whereas steady-state observations are not. Theoretically, steady-state is reached in the limit as time approaches infinity; however, there is a point in finite time where it can be assumed that a system is in steady-state. UAVSim can be used to perform both transient and steady-state analyses. An examination of results using steady-state will be performed in this chapter. The discussions presented show some but not all of the capabilities of UAVSim.

B. DETERMINATION OF STEADY-STATE.

In order to perform steady-state analysis, two questions have to be answered: "When does the system enter steady-state?" and "After how many runs should the simulation be terminated?" Determining steady-state is important in analysis of the MOPs because steady state is the point at which the observations of the MOP are no longer biased by the initial conditions.

We desire to provide estimates with a prescribed degree of accuracy. The objective is to obtain an accurate estimate of the true mean and an accurate confidence interval that covers the true mean [Ref. 26:p. 538]. To do such requires knowledge of how many replications or number of deployments that must be conducted in order to obtain a specified error in the estimate of the mean [Ref. 26:p. 536]. There are two methods to determine when to terminate

a simulation, absolute precision and relative precision. In this study, relative precision will be used and is entered as an input parameter.

Because of the options available in UAVSim, it was necessary to determine steady-state for both the continuous and non-continuous coverage cases. The method used was to graph the MOPs for different deployment lengths and by inspection determine the point at which the values of the MOP appear to "settle down."

For the continuous case, the primary MOP was ETOS. With inputs given in Table 5, and varying the length of deployment, the simulation appeared to reach steady-state after 230 days. Figure 12 shows a graph of simulation length vs. the value of ETOS. For this case, we will "warm up" the simulation for 230 days prior to collecting out steady-state output.

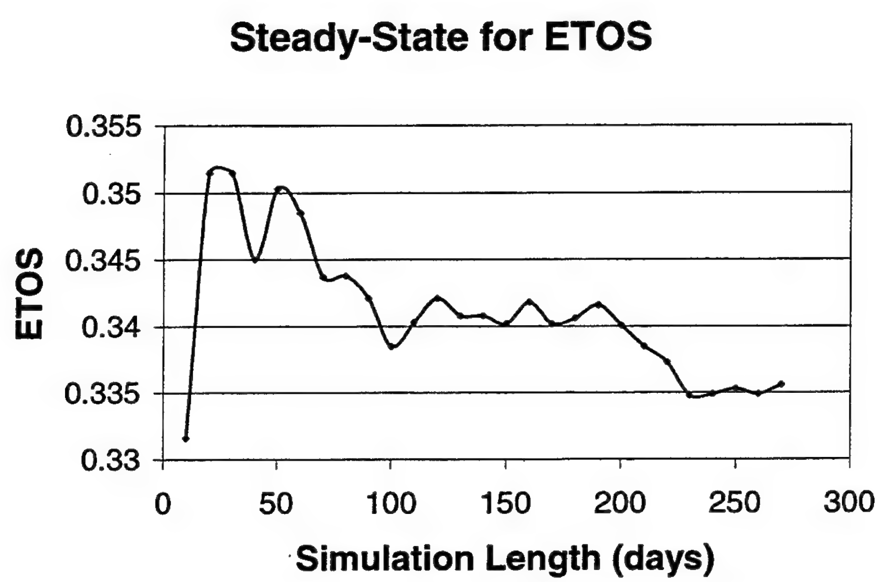

Figure 12: ETOS Steady-State

In the non-continuous case, there are two situations that could be studied. The first case (Case I) is when OPTEMPO constraints are active and the second case (Case II) is when surge constraints are active. In both cases, the MOP that required the longest simulation length to reach steady-state was "down time." The length of a simulation run was determined to be 360 and 450 respectively for Case I and Case II using inputs in Table 5. Figures 13 and 14 show the graphs of the MOPs vs. the length of simulation.

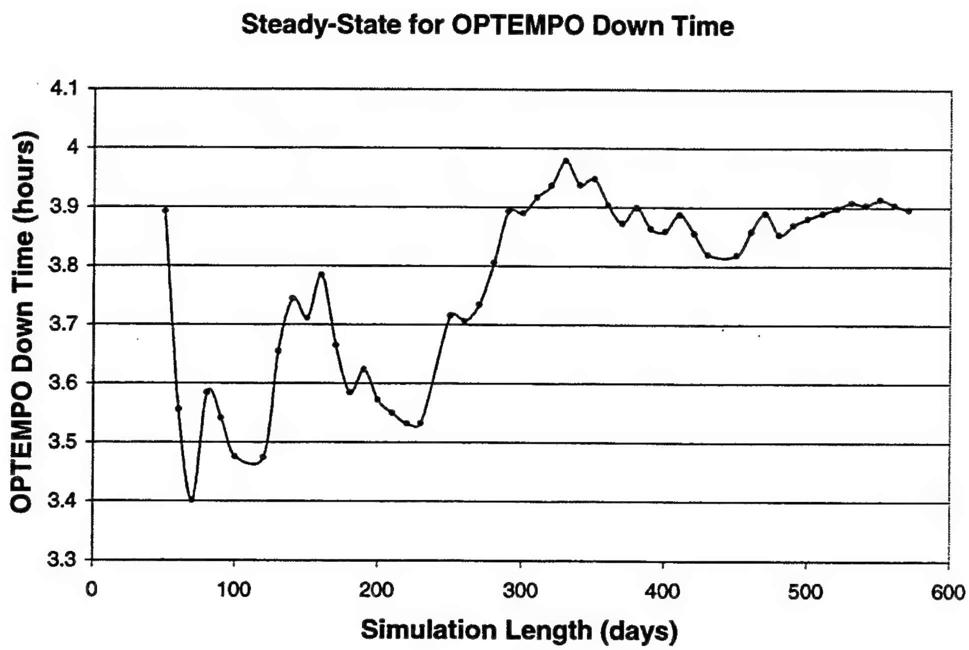

Figure 13: Steady-State for Optempo Down Time

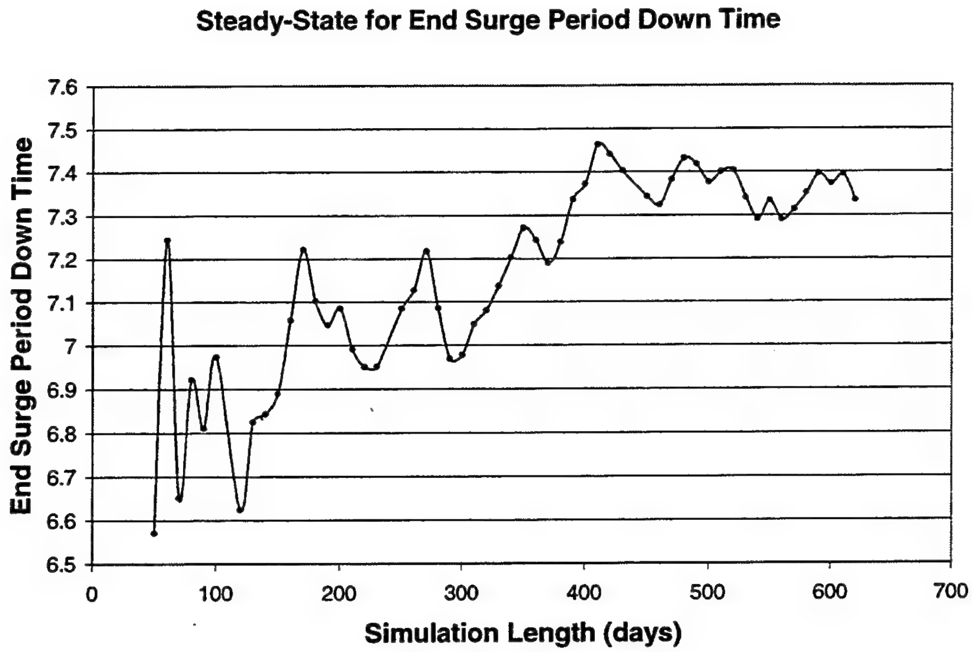

Figure 14: Steady-State for End Surge Period Down Time

C. CONTINUOUS AND NON-CONTINUOUS OPERATIONS.

UAVSim allows the analyst to examine continuous and non-continuous operations for UAVs. In this chapter both topics will be explored and the reader should note the context in which each applies. Continuous operations will be assumed to be operations at an Army division and higher level while non-continuous will be associated with brigade and below operations. The current version of the model is flexible enough to also examine operations at the Corps and higher levels. However, the focus of this study will be at division and brigade levels.

D. DIVISION OPERATIONS.

Interviews with members of the division intelligence staff at the 4^{th} Infantry Division, Fort Hood, Texas, indicate that there is a requirement at the division level to have continuous

coverage of an AO. There are several limiting factors which may affect the ability of a UAV company to provide such support, one of which is positioning. It is desired to position the company as far away from areas of hostile activity as possible for the purposes of force protection and still fulfill requirements. New weapons systems such as the Paladin artillery system and follow-ons, i.e. - Crusader, will allow the division to engage the enemy at much greater ranges. An immediate question is "What is the effective range of a UAV company?" The approach taken to answer this question was to vary positioning of a UAV system and compare the values for ETOS.

1. Positioning of a UAV Company.

Consider a scenario in which a division commander desires to have continuous coverage of an AO. The operations and intelligence sections of the division staff must determine where to position the UAV company so that it can effectively perform its mission. It seems logical that for limited UAV endurance, the value of ETOS would decrease as the ingress time increases (distance to the AO). This is synonymous with varying the distance from the launch and recovery site to the AO. Such analysis will provide the decision-maker with an indication of the proportion of time that a company of UAVs will cover the AO. The inputs for this analysis for a one hour ingress time are presented in Table 16. All of the distributions are assumed to be exponential.

Figure 15 shows the relationship between ingress time and ETOS. As the ingress time increases, the value of ETOS decreases. UAVs have a longer distance to fly in order to reach the AO and thus spend less time on station. This would be a planning consideration for staffs allocating UAVs for missions. ETOS would indicate the proportion of time that a company's baseline of UAVs could provide RSTA. For this scenario, positioning a UAV system so that

ingress time is about one hour would result in approximately 90% effectiveness; however, a commander requiring a greater percentage of coverage time may position the company thirty minutes from the AO.

```
SIMULATION Input data for \code\test1\1ie20maf.txt.out:
Number of platforms: 4
Number of maintenance paths: 1
Priority maintenance active: false
Wear and tear allowed on UAVs: false
Maintenance constraints active: false
Number of maintenance teams: 1
Maximum number of platforms in flight :2
GCS constraints active: false
Number of GCS crews: 1
Length of Warm Up Period (days): 230.0000
Planned Length of Deployment (days): 30.0000
Actual Length of Simulation (days): 260.0000
OPTEMPO constraints active: false
Deployment OPTEMPO (hours): 12.0000
Surge OPTEMPO constraints active: false
Surge OPTEMPO (hours): 8.0000
Ingress time (hours): 1.0000
Egress time (hours): 1.0000
Scheduled on station time (hours): 4.0000
Platform turn time (hours): 0.5000
Time to complete scheduled maintenance (hours): 7.0000
Mean repair time for each non-mission affecting failures (hours): 0.5000
Flight time between scheduled maintenance actions (hours): 50.0000
Mean time between non-mission affecting failures (hours): 5.0000
The z value used to calculate confidence intervals: 1.9600

DISTRIBUTIONS and Parameters:
Platform MAF Time: Exponential
Platform MAF Time Parameters: 20.0
Sensor Package MAF Time: Exponential
Sensor Package MAF Time Parameters: 110.0
Platform Repair Time: Exponential
Platform Repair Time Parameters: 2.0
Sensor Package Repair Time: Exponential
Sensor Package Repair Time Parameters: 2.0
Logistics Delay Time: Exponential
Logistics Delay Time Parameters: 0.5
Preventive Maintenance Time: Exponential
Preventive Maintenance Time Parameters: 0.5
```

Table 16: Inputs for Effect of Positioning on ETOS

There is a discussion of these inputs in Table 12.

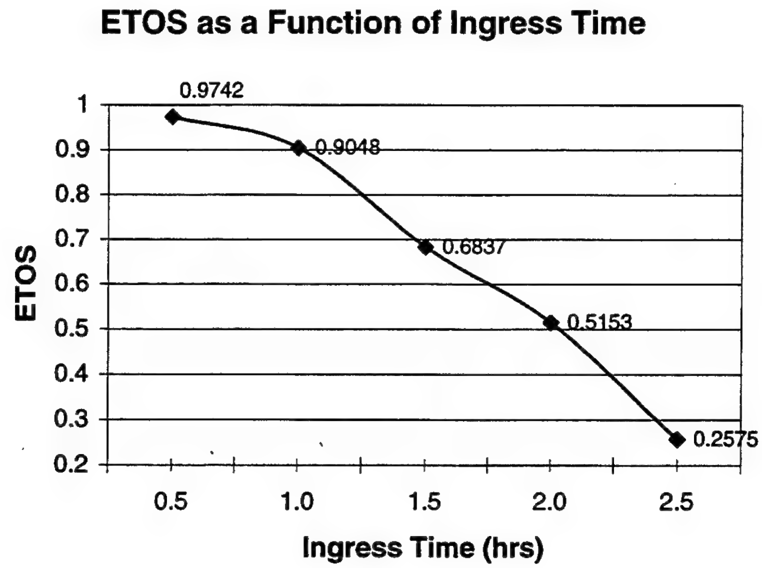

Figure 15: The Effect of Positioning on ETOS
The UAVs in this example each had a fixed endurance of 4 hours.

2. Endurance.

The previous example was a particular UAV System with a fixed endurance. Next, we examine multiple systems with differences in endurance. For illustrative purposes, assume that the goal is to achieve a 95% ETOS. We fix the ingress time at one hour and run the model with UAVs having different endurance capabilities. The inputs are the same as those shown in Table 16 with the exception that in each run of the model, a UAV system with a different endurance is used. Figure 16 shows the result of this analysis. A UAV system consisting of four platforms with an endurance of eight hours satisfies the goal.

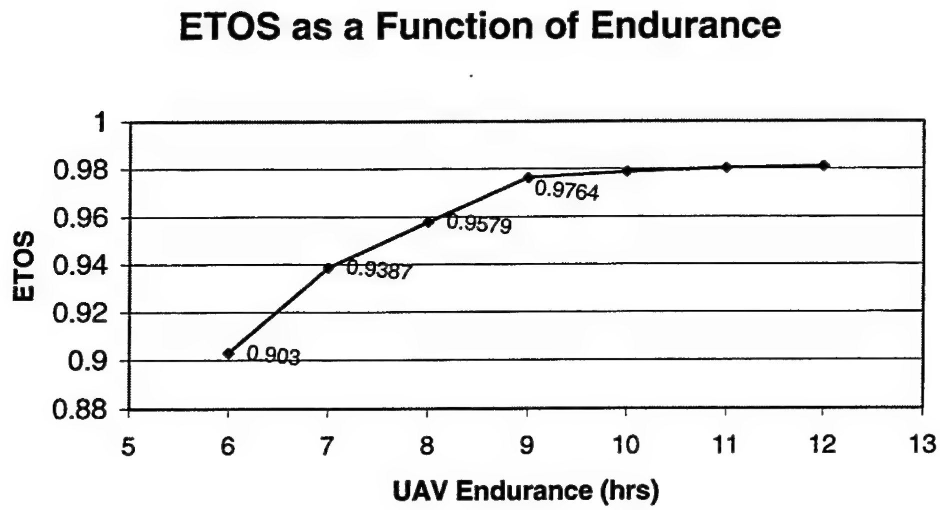

Figure 16: Systems with Different Endurance
The UAVs in this example each had a fixed ingress time of 1 hour.

3. The Benefit of Maintenance Prioritization.

There may be alternatives less costly than increasing the endurance of a UAV system. One alternative is to change the company maintenance policy. In a study conducted by Post and Warner, one of the questions that could not be answered using the MASS model was "Does priority maintenance optimize ETOS?" [Ref. 17]. Maintenance prioritization has been added as an option to UAVSim and now it is possible to address this issue. The same inputs used in the previous example, Table 16, are used here with the exception that now maintenance is prioritized in an effort to improve ETOS. Figure 17 shows a comparison of ETOS as a function of priority and non-priority maintenance.

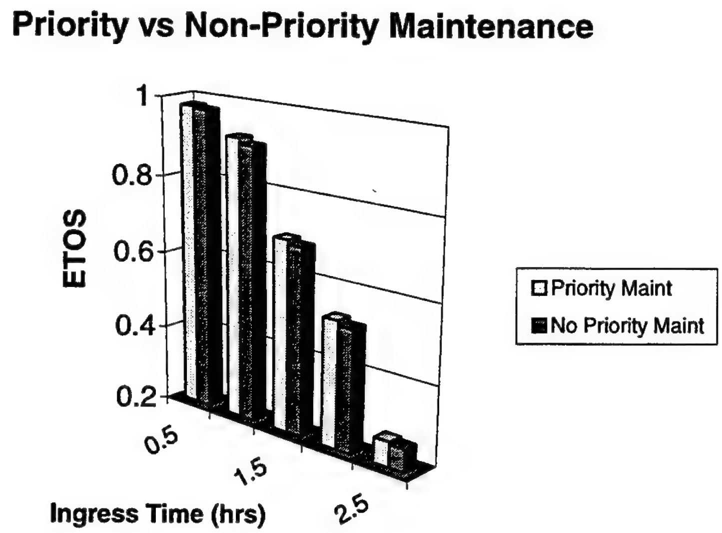

Figure 17: Benefit of Priority Maintenance

There is no noticeable benefit associated with using priority maintenance. This result is similar to that proposed in "Operational Analysis of Sustainability of a Mobile Military Platform" [Ref. 27:p. 23]. In that study, the effect of maintenance repair times on ETOS was examined. From that comparison, it was hypothesized that ETOS was not sensitive to changes in the company's maintenance structure. These findings support that hypothesis. These findings suggest that money and/or other resources may be better used by not investing in prioritizing maintenance. One possible explanation for this lack of sensitivity to prioritization is that UAVs typically spend a relatively short amount of time in maintenance or waiting for maintenance. For a one hour ingress time, the mean wait time for maintenance was 1.7914 hours and 1.5950 hours for non-priority and priority maintenance respectively. This only resulted in a 10.96% or 12 minute decrease in wait time. In relation to the total cycle time, a decrease of 12 minutes does not make a practically significant difference.

4. Number of Maintenance Paths.

It seems plausible that increasing the number of maintenance paths would decrease the amount of time that UAVs are not able to fly and thus increase the value of ETOS. The effect of increasing the number of maintenance paths will be explored here. The method used was to vary the number of available maintenance paths from one to four while keeping all other factors constant (in particular, 4 UAVs) and evaluating the resulting values of ETOS. Each maintenance path had its own maintenance crew with no limitations. The following figure illustrates the benefit associated with increasing the number of maintenance paths.

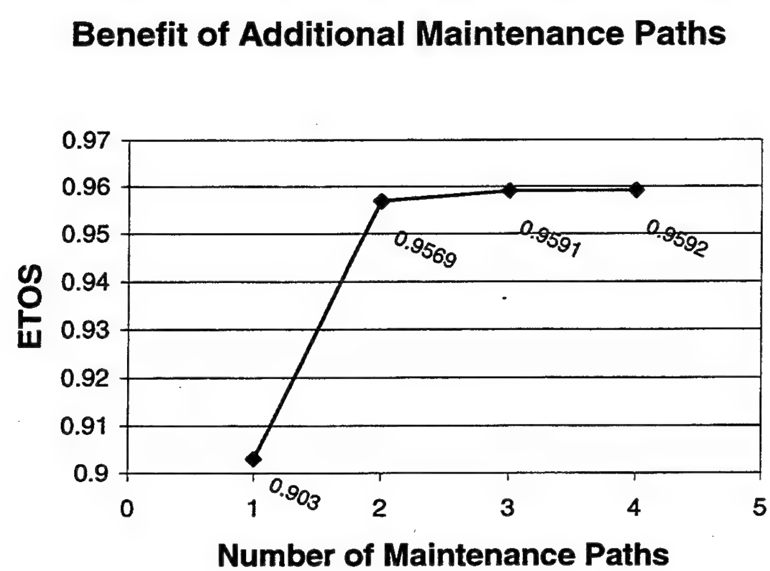

Figure 18: Number of Maintenance Paths
The number of UAVs was held constant at 4 in this example. Each maintenance path did not have crew-related limitations.

The gain associated with increasing from one to two maintenance paths is significant. However, additional maintenance paths do not improve ETOS.

E. DISTRIBUTIONS AND ETOS.

Thus far, explorations have been performed with the assumption that all distributions within the model are exponential. But, what if the distributions are not exponential? How does the distribution affect the value of ETOS and is the model sensitive to changes in the distributions?

UAVSim is very flexible in that the analyst can specify the distribution for any of the random times. Not only can any distribution that already exists in the model be used but distributions can be created and added as well. A major point is that the model does not have to be modified or recompiled in order to use or add a different distribution; moreover, the model remains unchanged. This is a major benefit of using a language such as Java and the component approach for modeling and simulation. With such a feature, the user is much better equipped to perform "what if " analyses.

To demonstrate this ability, Sculptured (a), Sculptured (b), and Triangular distributions were implemented and used in a comparison with the exponential and Weibull. We chose these to illustrate the flexibility of UAVSim, and not because they are necessarily UAV failure distributions.

1. Sculptured(a) and Sculptured(b) Distributions.

Both of the Sculptured distributions were developed and explained in "Distribution Sculpturing or Inverse Modification" [Ref. 28:pp. 36-44]. These distributions are derived from the exponential distribution but have different effects. They produce more short MAF times than the exponential although the mean is the same as the exponential. This results in a heavier right hand tail.

The algorithm coded and implemented for the Sculptured distributions is presented in APPENDIX E. Even though the algorithm was from a published source, we verified its implementation. The method used to verify that these two distributions were producing correct results was to first generate the value of the parameter of the distribution so as to have the same mean as the exponential. The value of MTBMAF used was the objective value, 20 hours. Next, 1000 random variates were generated and a histogram of those observations created. The mean of the empirical data was calculated and then compared with the true mean.

Table 17 shows the values of the parameters the Sculptured and other distributions that were used in this comparison. The reader should note that all distributions were parameterized so that the theoretical mean would be the same. The exponential, Sculptured(a) and Sculptured(b) are one parameter distributions. Once a mean is selected, the user has no control over the variance.

Distribution	Mean (hrs)	Empirical Mean	Empirical Variance	Parameters
Exponential	20.0	19.82	1848.16	$\lambda = 1/20$ (rate)
Weibull	20.0	19.89	1935.12	$\alpha = 0.5, \beta = 10$
Sculptured(a)	20.0	19.81	1742.33	$\alpha = 9.5$
Sculptured(b)	20.0	19.46	9916.76	$\alpha = 0.7917$
Triangular	20.0	19.93	194.55	$a = 0.0, b = 60.0, c = 0.0$

Table 17: Parameters for Distributions

The reader should note that for both Sculptured distributions, the empirical mean is very close to the theoretical. An exploration in which 10,000 and 20,000 variates were generated and the empirical mean calculated confirmed that there is only a small difference in the theoretical and empirical means.

2. Triangular Distribution.

The Triangular distribution was created and used in this analysis because it is often used for a rough estimate where there is a limited amount of data [Ref. 26:p. 343]. There are three basic types of the triangular distribution: right, left, and general. All three of these distributions were added and are available in UAVSim; however, the general form of the distribution can be parameterized such that it can generate variates for all types. In this comparison, it was hypothesized that the Right Triangular would be appropriate.

3. Results and Comparison.

Table 18 shows the values of the input parameters for the Sculptured(b) MTBMAF, one of these cases used in this comparison. The only variation for the data presented is that the MAF distribution and parameters were changed for each run.

```
SIMULATION Input data for \code\test14\sculpB.txt.out:
Number of platforms: 4
Number of maintenance paths: 1
Priority maintenance active: true
Wear and tear allowed on UAVs: false
Preventive Maintenance Effectiveness: 0.0
Maintenance constraints active: false
Number of maintenance teams: 1
Maximum number of platforms in flight :2
GCS constraints active: false
Number of GCS crews: 1
Length of Warm Up Period (days): 230.0000
Planned Length of Deployment (days): 30.0000
Actual Length of Simulation (days): 260.0000
OPTEMPO constraints active: false
Deployment OPTEMPO (hours): 12.0000
Surge OPTEMPO constraints active: false
Surge OPTEMPO (hours): 8.0000
Ingress time (hours): 1.0000
Egress time (hours): 1.0000
Scheduled on station time (hours): 4.0000
Platform turn time (hours): 0.5000
Time to complete scheduled maintenance (hours): 7.0000
Mean repair time for each non-mission affecting failures (hours): 0.5000
Flight time between scheduled maintenance actions (hours): 50.0000
Mean time between non-mission affecting failures (hours): 5.0000
The z value used to calculate confidence intervals: 1.9600

DISTRIBUTIONS and Parameters:
Platform MAF Time: SculpturedB
Platform MAF Time Parameters: 0.7917
Sensor Package MAF Time: Exponential
Sensor Package MAF Time Parameters: 110.0
Platform Repair Time: LogNormal
Platform Repair Time Parameters: 0.6616225 0.2510964
Sensor Package Repair Time: LogNormal
Sensor Package Repair Time Parameters: 0.6616255 0.2510964
Logistics Delay Time: LogNormal
Logistics Delay Time Parameters: -0.7246719 0.2510964
Preventive Maintenance Time: LogNormal
Preventive Maintenance Time Parameters: -0.6983266 0.107785
```

Table 18: Input Parameters for Comparison

Table 19 shows the mean values for ETOS and the 95% confidence intervals. Figure 19 illustrates the differences in the observed values of ETOS for each of the distributions.

Distribution	Mean ETOS	ETOS 95% Confidence Interval
Exponential	0.9280	0.9179 - 0.9381
Weibull	0.7600	0.7312 - 0.7888
Sculptured(a)	0.7741	0.7509 - 0.7973
Sculptured(b)	0.4427	0.3984 - 0.4870
Triangular	0.9356	0.9213 - 0.9499

Table 19: Results of Comparison

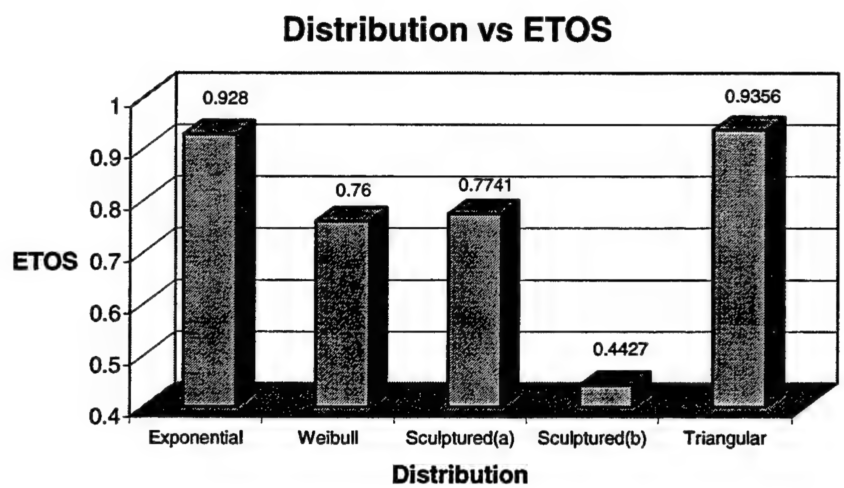

Figure 19: The Effect of Various MAF Distributions

This demonstrates that the user can select or create any distribution desired for analysis. The distribution assumed has a significant impact on the resulting value of ETOS. In this example, only the first moment for each of the distributions could be matched. The empirical mean and variance are shown in Table 19. The empirical means are relatively close. However, there are large differences in the empirical variances. If it were possible to match the first and second moments of these distributions, a stronger statement about the relationship between the distribution and ETOS could be made. It is recommended that during the testing of UAVs, data on the failure times be collected so that statisticians can determine the true

distribution of MAFs. Decisions made without a good approximation of the true distribution may result in drastic overestimates or underestimates. For example, decisions based on analysis assuming that the MAF times are exponential result in approximately a 16% overestimate if the true distribution were the Weibull of our example. The effect for the division commander is that approximately 16% of the time when he expected to have coverage of the AO, he would not.

F. VARIANCE OF TIME TO MAF.

The ORD for the brigade commander's UAV lists several objective and threshold values for a proposed system. The value that is listed is a mean or average. Yet, is specification of the mean value enough? It is hypothesized that only specifying the mean is not enough. A stipulation on variance should also be given. For cases in which the time to a MAF fits the exponential distribution or another one-parameter distribution, a mean is sufficient. Knowing the mean for a one-parameter distribution such as the exponential implies knowledge of the variance. However, if the appropriate distribution is not the exponential but a two-parameter distribution such as the Weibull, then specification of only the mean is not enough. This is an important issue since engineers may design a UAV system to meet a certain MTBMAF, but a large variance may have significant effects on performance.

The Weibull distribution is often used to model times to failure for mechanical equipment [Ref. 26:p. 333]. For the next examples, we assume the MAF time follows the Weibull distribution. The Weibull requires two parameters: the scale parameter that will be referred to as β and a shape parameter α. If the distribution of platform MAF times is Weibull, significant differences in results can occur compared to the exponential distribution even though the mean is equal to that specified in the ORD.

1. Values of α and β.

Values for the parameters of a Weibull distribution with a mean equal to the objective and threshold values, 20 and 54 hours respectively, were calculated. The values for α and β are calculated for increasing hazard rates ($\alpha > 1$) and decreasing hazard rates ($\alpha < 1$). Graphs of the distributions are shown in APPENDIX D. The Weibull with $\alpha = 1$ is an exponential with $\lambda = 1/\beta$.

Parameter				
Mean	α	β	**Mean (hrs)**	**Variance (hrs^2)**
Threshold, 20 hrs	0.25	0.8333	20.0	27600.01
	0.75	16.7977	20.0	732.09
	1.25	21.4734	20.0	259.21
	1.75	22.4563	20.0	139.12
Objective, 54 hrs	0.25	2.2500	54.0	201204.01
	0.75	45.3537	54.0	5336.96
	1.25	57.97825	54.0	1889.65
	1.75	60.63207	54.0	1014.17

Table 20: Moments for Various Weibull Distributions

2. ETOS Sensitivity to Variance.

To demonstrate the effect of IFR and DFR on ETOS, the scenario previously discussed will be revisited. The performance of a UAV system was examined using four possible failure rates. The inputs for the simulation are shown in Table 21. The reader should note that the only input that was changed on each run was the vector of parameters for the platform MAF. Four values for α and the corresponding β's were calculated and used. These values yield theoretical means that are the same as specified in the ORD. The ETOS was determined so that the commander could have an indication of the percentage of time that the UAV company could provide RSTA.

```
SIMULATION Input data for \code\test3\pt5-plusMinus5.txt.out:
Number of platforms: 4
Number of maintenance paths: 1
Priority maintenance active: true
Wear and tear allowed on UAVs: false
Preventive Maintenance Effectiveness: 0.0
Maintenance constraints active: false
Number of maintenance teams: 1
Maximum number of platforms in flight :2
GCS constraints active: false
Number of GCS crews: 1
Length of Warm Up Period (days): 230.0000
Planned Length of Deployment (days): 30.0000
Actual Length of Simulation (days): 260.0000
OPTEMPO constraints active: false
Deployment OPTEMPO (hours): 12.0000
Surge OPTEMPO constraints active: false
Surge OPTEMPO (hours): 8.0000
Ingress time (hours): 1.0000
Egress time (hours): 1.0000
Scheduled on station time (hours): 4.0000
Time to complete scheduled maintenance (hours): 7.0000
Mean repair time for each non-mission affecting failures (hours): 0.5000
Flight time between scheduled maintenance actions (hours): 50.0000
Mean time between non-mission affecting failures (hours): 5.0000
The z value used to calculate confidence intervals: 1.9600

DISTRIBUTIONS and Parameters:
Platform MAF Time: Weibull
Platform MAF Time Parameters: 0.25 0.8333
Sensor Package MAF Time: Exponential
Sensor Package MAF Time Parameters: 110.0
Platform Repair Time: LogNormal
Platform Repair Time Parameters: 0.6616225 0.2510964
Sensor Package Repair Time: LogNormal
Sensor Package Repair Time Parameters: 0.6616255 0.2510964
Logistics Delay Time: LogNormal
Logistics Delay Time Parameters: -0.7246719 0.2510964
Preventive Maintenance Time: LogNormal
Preventive Maintenance Time Parameters: -0.6983266 0.107785
```

Table 21: Input Values for Scenario

The values of ETOS are shown in Table 22 along with a 95% confidence interval.

Mean (hrs)	Variance (hrs^2)	ETOS	95% Confidence Interval
20.0	27600	0.3921	0.3460 - 0.4383
20.0	732	0.8770	0.8629 - 0.8912
20.0	259	0.9536	0.9416 - 0.9656
20.0	139	0.9757	0.9663 - 0.9851

Table 22: Parameters for Weibull

The variance of the time to a MAF does effect the value of ETOS, even though the mean is held constant and the same distribution (Weibull) was used. As the variance decreased, the associated ETOS increased because the platforms flew longer without a MAF. Thus the company is better able to meet the commander's requirement. We conclude that specification of a MTBMAF may not be sufficient and that the ORD should also specify a variance of time between mission affecting failures.

G. INCREASING THE MTBMAF.

A comparison can also be performed using the threshold value for MTBMAF. The inputs to the model were kept the same with the exception of the parameters for the Weibull distribution. Figure 20 shows this comparison and also shows the benefit of increasing MTBMAF from the threshold to the objective value. As was expected, the higher MTBMAF would increase the company's ability to support the commander. However, there does not appear to be a significant increase.

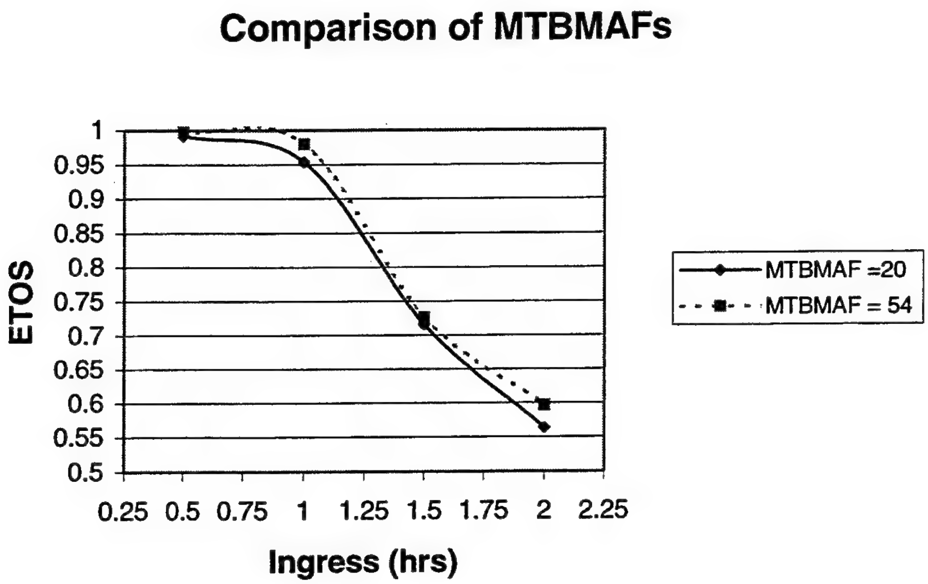

Figure 20: Comparison of Values for MTBMAF

H. EFFECT OF NON-PERFECT MAINTENANCE.

Thus far, analysis has been performed assuming that the maintenance section will perform "perfect maintenance." This assumption is unrealistic. It is quite possible and probable that a maintenance crew will not discover and fix every deficiency on a piece of equipment. In other words, "non-perfect maintenance" will exist. A discussion of how this type of maintenance was modeled is presented in Chapter III. The inputs for this comparison are the same as those given in Table 21 with the exception that the option "wear and tear allowed on UAVs" was set to true. The results of this comparison are shown in Figure 21.

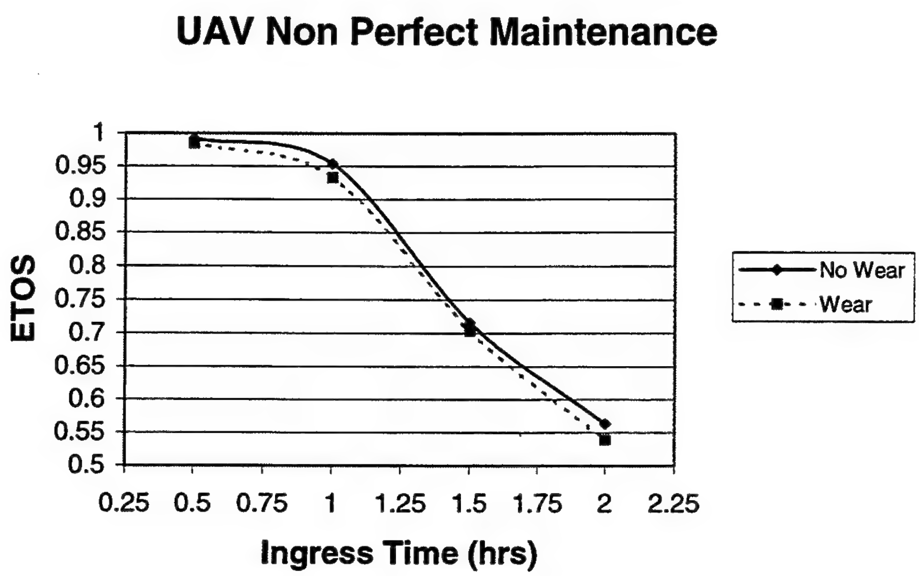

Figure 21: Effect of Non-Perfect Maintenance

Allowing non-perfect maintenance does decrease performance; however, there is not a drastic difference in performance.

I. BRIGADE OPERATIONS.

Thus far, the analysis has focused on division operations with continuous operation of a UAV company. Now the focus will be shifted to brigade operations. The brigade has fewer UAV assets than were available at the division level primarily because the AO for a brigade is approximately one-third of a division's. The requirement for UAV support at this level is projected to be twelve hours of continuous coverage versus the twenty-four. Initially, the reliability of the UAV will be examined and the remaining analysis will be on the structure of the company. ETOS is no longer the most appropriate MOP. The expected number of hours to achieve OPTEMPO will be evaluated.

Thus far in this study, the value for sensor package MTBMAF has been the threshold value, 110 hours. However, as with other parameters in the ORD, an objective value is presented as well. This value for sensor MTBMAF is 160 hours. A question of interest might be: "Is there a benefit associated with increasing the MTBMAF for sensors?" The exponential distribution is often used to model the time to failure for electronic equipment and is used here as well.

We run the simulation with platforms having sensor MTBMAFs of 110 and 160 hours and compare hours to achieve OPTEMPO. The inputs are shown in Table 23. All inputs were held constant with the exception of the parameter for the sensor package failure distribution. Figure 22 shows the results.

```
SIMULATION Input data for \code\test12\1pt5-mtbmaf160.txt.out:
Number of platforms: 4
Number of maintenance paths: 1
Priority maintenance active: true
Wear and tear allowed on UAVs: true
Preventive Maintenance Effectiveness: 0.0
Maintenance constraints active: false
Number of maintenance teams: 1
Maximum number of platforms in flight :2
GCS constraints active: false
Number of GCS crews: 1
Length of Warm Up Period (days): 360.0000
Planned Length of Deployment (days): 30.0000
Actual Length of Simulation (days): 390.0000
OPTEMPO constraints active: true
Deployment OPTEMPO (hours): 12.0000
Surge OPTEMPO constraints active: false
Surge OPTEMPO (hours): 8.0000
Ingress time (hours): 1.5000
Egress time (hours): 1.5000
Scheduled on station time (hours): 3.0000
Platform turn time (hours): 0.5000
Time to complete scheduled maintenance (hours): 7.0000
Mean repair time for each non-mission affecting failures (hours): 0.5000
Flight time between scheduled maintenance actions (hours): 50.0000
Mean time between non-mission affecting failures (hours): 5.0000
The z value used to calculate confidence intervals: 1.9600

DISTRIBUTIONS and Parameters:
Platform MAF Time: Weibull
Platform MAF Time Parameters: 0.75 16.7977
Sensor Package MAF Time: Exponential
Sensor Package MAF Time Parameters: 160.0
Platform Repair Time: LogNormal
Platform Repair Time Parameters: 0.6616225 0.2510964
Sensor Package Repair Time: LogNormal
Sensor Package Repair Time Parameters: 0.6616255 0.2510964
Logistics Delay Time: LogNormal
Logistics Delay Time Parameters: -0.7246719 0.2510964
Preventive Maintenance Time: LogNormal
Preventive Maintenance Time Parameters: -0.6983266 0.107785
```

Table 23: Input Data for Sensor MTBMAF Comparison

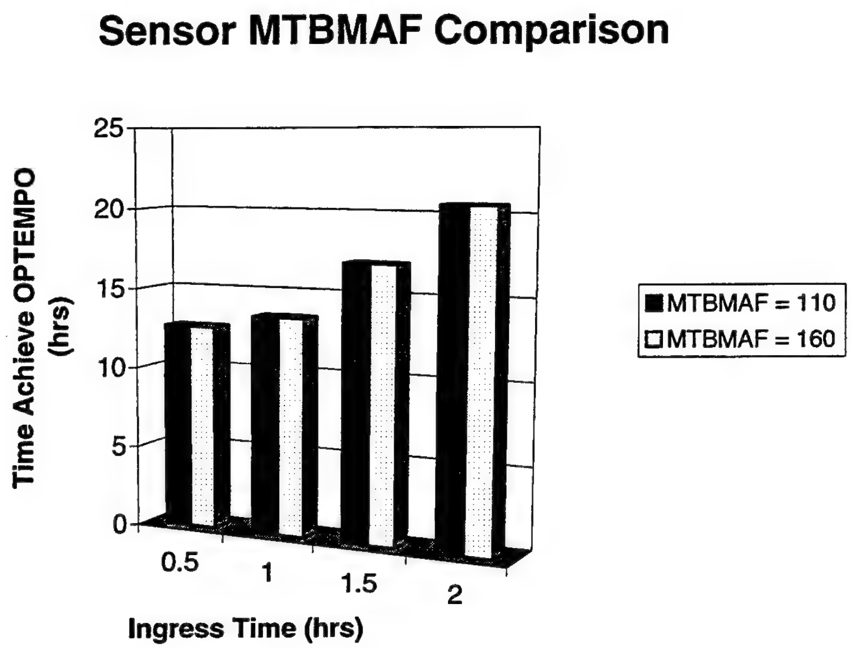

Figure 22: Benefit of Increasing Sensor MTBMAF

By increasing the MTBMAF from 110 to 160 hours, there is no noticeable difference in time to meet the OPTEMPO requirement. This analysis indicates that sensor MTBMAF may have very little or no effect on fulfilling the coverage requirement. One possible explanation is that because the MTBMAF for platforms is so low, that sensor failures rarely affect performance of the UAV.

J. BRIGADE UAV COMPANY STRUCTURE.

"How many UAVs are enough?" There is no one correct answer to this question. In brigade operations, this number is driven by at least two factors: OPTEMPO requirement and endurance. This suggests that the best UAV system should be flexible enough to handle the range of operations that a brigade UAV company is expected to face.

1. Number of UAVs.

The first analysis will be an exploration into the number of UAVs required to fulfill a commander's requirement to maintain a 12-hour OPTEMPO. Consider a scenario in which a brigade commander desires to have 12 hours per day of continuous coverage. How many UAVs does he need? We present an example of using UAVSim to determine a possible solution.

Runs of the simulation were conducted holding OPTEMPO constant; however, the number of UAVs employed ranges from 1 to 6 each. The MOP examined was hours to achieve OPTEMPO. There is a startup cost associated with meeting an OPTEMPO, the ingress time. The objective is to provide coverage with the total time required to do so being as close as possible to the sum of the ingress time and the coverage requirement. The following figure shows the relationship between the number of UAVs and the number of hours required to meet a twelve-hour OPTEMPO.

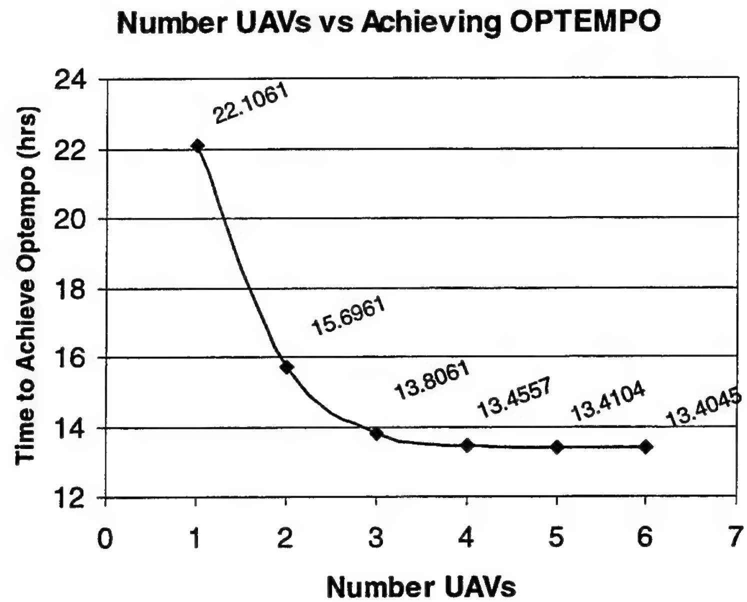

Figure 23: UAVs to Achieve OPTEMPO

Figure 23 indicates that for a twelve hour OPTEMPO, at most four UAVs would be needed. After four UAVs there is very little if any gain.

2. UAV Endurance.

The second factor mentioned as a factor in determining the number of UAVs was endurance of the platforms. A platform cannot fly forever. Limiting factors include the need for fuel and time intervals between maintenance. As such, UAVs have a set endurance that is defined as the amount of time that a UAV can fly between launch and landing. It may seem that more is better, but the real question is: "How much is enough?" The following example demonstrates the ability to use UAVSim as an analysis tool to try to get an answer.

Runs of the simulation were performed in which all input parameters were the same with the exception of endurance; the sum of the planned ingress time, time on station, and egress time remained constant. The input parameters are shown in Table 24.

```
SIMULATION Input data for \code\test9\5endurance2uav.txt.out:
Number of platforms: 2
Number of maintenance paths: 1
Priority maintenance active: true
Wear and tear allowed on UAVs: true
Preventive Maintenance Effectiveness: 0.0
Maintenance constraints active: false
Number of maintenance teams: 1
Maximum number of platforms in flight :2
GCS constraints active: false
Number of GCS crews: 1
Length of Warm Up Period (days): 360.0000
Planned Length of Deployment (days): 30.0000
Actual Length of Simulation (days): 390.0000
OPTEMPO constraints active: true
Deployment OPTEMPO (hours): 12.0000
Surge OPTEMPO constraints active: false
Surge OPTEMPO (hours): 8.0000
Number of simulated deployments: 1
Ingress time (hours): 1.0000
Egress time (hours): 1.0000
Scheduled on station time (hours): 5.0000
Platform turn time (hours): 0.5000
Time to complete scheduled maintenance (hours): 7.0000
Mean repair time for each non-mission affecting failures (hours): 0.5000
Flight time between scheduled maintenance actions (hours): 50.0000
Mean time between non-mission affecting failures (hours): 5.0000
The z value used to calculate confidence intervals: 1.9600

DISTRIBUTIONS and Parameters:
Platform MAF Time: Weibull
Platform MAF Time Parameters: 0.75 16.7977
Sensor Package MAF Time: Exponential
Sensor Package MAF Time Parameters: 110.0
Platform Repair Time: LogNormal
Platform Repair Time Parameters: 0.6616225 0.2510964
Sensor Package Repair Time: LogNormal
Sensor Package Repair Time Parameters: 0.6616255 0.2510964
Logistics Delay Time: LogNormal
Logistics Delay Time Parameters: -0.7246719 0.2510964
Preventive Maintenance Time: LogNormal
Preventive Maintenance Time Parameters: -0.6983266 0.107785
```

Table 24: Input Data for Endurance Comparison

Figure 24 shows the results of this comparison. The return for increasing the number of hours of endurance decreases substantially after the increase from six to seven hours. As can be seen, there is very little return after six hours. Thus, for an OPTEMPO requirement of 12 hours, a baseline of 4 UAVs each with an endurance of 6 hours appears to be a sound alternative.

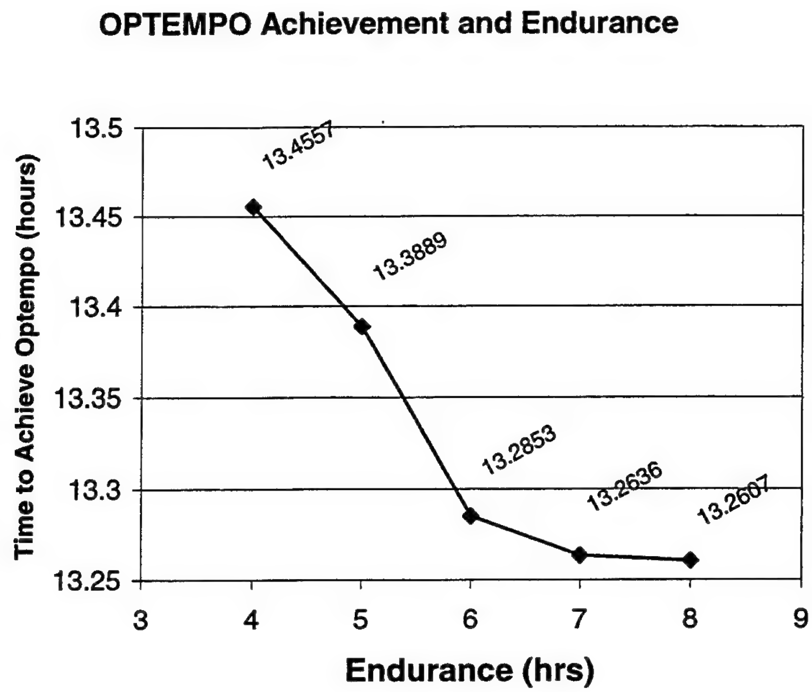

Figure 24: Benefit of UAV Endurance

K. ANALYSIS OF ALTERNATIVES.

For the next example, we assume that an acquisition decision must be made about three UAV systems. Furthermore, developers have data that can be input into UAVSim. Analysts can use this model to evaluate the systems and compare their performance. For the purposes of this example, three hypothetical systems are to be evaluated, and each system has different capabilities. Table 25 shows the major differences in the systems. One of the systems examined had characteristics equivalent to the objective values listed in the ORD.

System	Endurance (hrs)	MTBMAF (hrs)	Number Maintenance Paths
UAV - ORD	6	20	1
UAV - B	8	60	2
UAV - C	10	40	1

Table 25: Characteristics of Systems

In the runs of the simulation, the ingress time was held constant for each of the systems so that the mission requirement would be identical. The question that must be answered is: "Which UAV system performs best?" An example of one of the input files is shown in Table 26. Table 27 gives the mean ETOS and 95% confidence interval and Figure 25 gives a graphical depiction of the ETOS obtained with each system.

```
SIMULATION Input data for \code\test15\alt1.txt.out:
Number of platforms: 4
Number of maintenance paths: 2
Priority maintenance active: true
Wear and tear allowed on UAVs: true
Preventive Maintenance Effectiveness: 0.0
Maintenance constraints active: false
Number of maintenance teams: N/A
Maximum number of platforms in flight :2
GCS constraints active: false
Number of GCS crews: 1
Length of Warm Up Period (days): 360.0000
Planned Length of Deployment (days): 30.0000
Actual Length of Simulation (days): 390.0000
OPTEMPO constraints active: false
Deployment OPTEMPO (hours): 12.0000
Surge OPTEMPO constraints active: false
Surge OPTEMPO (hours): 8.0000
Ingress time (hours): 1.0000
Egress time (hours): 1.0000
Scheduled on station time (hours): 6.0000
Platform turn time (hours): 0.5000
Time to complete scheduled maintenance (hours): 7.0000
Mean repair time for each non-mission affecting failures (hours): 0.5000
Flight time between scheduled maintenance actions (hours): 50.0000
Mean time between non-mission affecting failures (hours): 5.0000
The z value used to calculate confidence intervals: 1.9600

DISTRIBUTIONS and Parameters:
Platform MAF Time: Weibull
Platform MAF Time Parameters: 0.75 50.393093
Sensor Package MAF Time: Exponential
Sensor Package MAF Time Parameters: 110.0
Platform Repair Time: LogNormal
Platform Repair Time Parameters: 0.6616225 0.2510964
Sensor Package Repair Time: LogNormal
Sensor Package Repair Time Parameters: 0.6616255 0.2510964
Logistics Delay Time: LogNormal
Logistics Delay Time Parameters: -0.7246719 0.2510964
Preventive Maintenance Time: LogNormal
Preventive Maintenance Time Parameters: -0.6983266 0.107785
```

Table 26: Input Data for Analysis of Alternatives

Maintenance constraints were not active. Therefore, each maintenance path had its own maintenance team with no limitations.

System	Mean ETOS	ETOS 95% Confidence Interval
UAV - ORD	0.9236	0.9080 - 0.9391
UAV - B	0.9903	0.9869 - 0.9939
UAV - C	0.9844	0.9759 - 0.9928

Table 27: Result of Analysis of Alternatives

By inspection, the confidence intervals for UAV B and UAV C overlap and suggest that there is no significant difference between the two systems' mean ETOS.

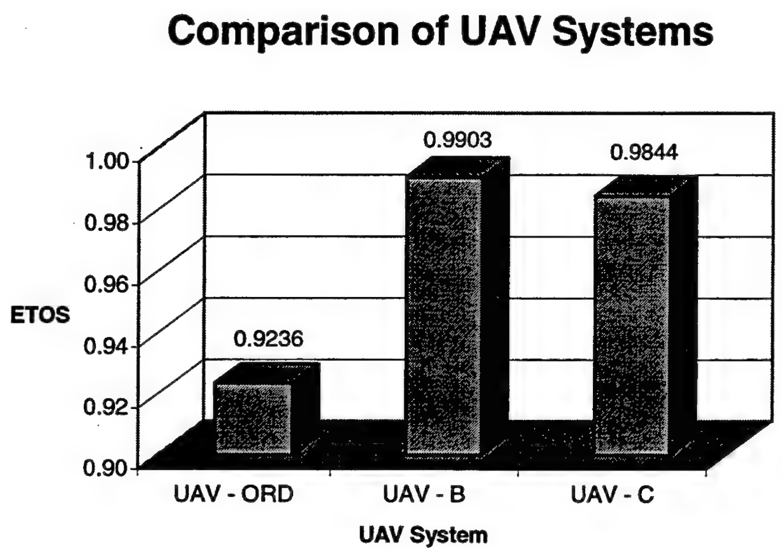

Figure 25: Comparison of Alternatives

Based on the values of ETOS, it appears that all of the systems perform relatively well. However, UAV B has the best performance. While UAVSim can be used as analysis tool to assist decision-makers it should not be the sole tool. For example, although UAV - B

had the best performance, a cost analysis of UAV B and UAV C or other selection criteria may result in C being selected as the best system.

L. SUMMARY.

This chapter has demonstrated several uses of an expandable, stochastic, discrete-event simulation, UAVSim, to support SBA and doctrinal analysis. UAVSim can be used to determine values of parameters to enhance performance, to determine if enhancement is possible, and also to determine points of diminishing return. Our analysis also indicated that specification of only a mean value for MTBMAF in the ORD might not be sufficient for reliable performance. The flexibility and reusability of this simulation have also been shown. The analyst can choose from a variety of distributions to use for all of the stochastic variables within the model or add his own. This model can also be used for analysis of alternatives, offering substantial benefit to the STEP of SBA as it applies to UAVs.

V. RECOMMENDATIONS.

A. GENERAL.

The model developed in this thesis is designed to serve as a basis for additional analysis involving the TUAV and other aerial platforms. The comparisons shown provide examples of how this model could be used to answer specific questions during the acquisition process, provide indications of performance during operational missions, and the effectiveness of changes in system structure. This model has been designed for use during all phases of the acquisition process and is flexible enough for the analyst to perform a variety of "what if" analyses. Perhaps one of the most substantial benefits of a model such as UAVSim is that it is coded in Java which allows a variety of extensible applications. This simulation is by no means all encompassing and can be improved upon. This chapter discusses general areas within the model that warrant further development and provides topics for further study.

B. MODEL IMPROVEMENT.

Because this model was designed to serve as a basis for further analysis, the list of possible improvements is endless. The topics listed below are some of the more important possible improvements.

1. Various Aerial Platforms.

This study has focused on the use of UAVSim for the analysis of TUAVs; however, it can be used in the analysis of other UAVs as well. The structure of this simulation is such that it can be easily expanded for use with virtually all types of UAVs. Moreover, it can be expanded for analysis of manned aircraft as well, such as the Commanche Helicopter.

2. Four Dimensions.

The flight of UAVs within the current version of the model is based only on time. At any specific instance, an exact location of an entity cannot be determined by geographical reference. The addition of geographic coordinates along with time will allow more robust analysis. This type of enhancement will further facilitate the realism associated with a combat scenario.

3. Area Search and Detection.

This simulation does not model area search or the detection of targets. The search and detection process is detailed and complex. An implicit detection methodology could be used; however, this model would benefit from the explicit representation of search and detection in the evaluation of the performance of UAVs once a geo-reference is incorporated. ETOS is not a measure of the effectiveness of a UAV's search and detection capability.

C. TOPICS OF FURTHER STUDY.

While conducting research for and performing this study, several topics of interest were identified. The following list identifies several of these topics.

1. Effectiveness of UAV Sensors.

Perhaps the ultimate question that a commander would like the answer to when it comes to a new system is "How effective is this system?" The work that has been done in this study can be used as a basis for further study in the effectiveness of UAVs. A proposed methodology would be to build a combat scenario and link an expanded version of UAVSim to it. The expanded version of UAVSim should be capable of the detection of targets and sending that information to firing units.

There is a two-fold benefit for such a study. One, it would provide an approximate indication of the effectiveness of a UAV system in a particular combat scenario. Secondly, it would provide a means for determining sensor-shooter timelines.

2. Sensor-Shooter Timeline.

Often the difference in hitting and missing a target on the battlefield is the timeliness in which the target is prosecuted. Such a study would provide an approximate indication of the timeliness in which a target must be engaged. Furthermore, it might suggest changes in training and TTP. In the training arena, such a study may indicate the need for greater proficiency for operators in passing information from sensor to shooter. Still yet, it may suggest changes in the manner in which targets are engaged.

3. Dynamic Retasking.

While conducting research at the 4th Infantry Division, FT Hood, Texas, I found that one of the recurring topics in the use of UAVs was dynamic retasking. Dynamic retasking is the unplanned diversion of a UAV to perform another mission. Several members of the division staff were interested in the effect of dynamic retasking given a limited number of UAVs which have limited hours of endurance.

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VI. SUMMARY

This thesis has demonstrated the development and use of an expandable, stochastic discrete-event simulation, UAVSim. This model was developed on a personal computer using Java and the discrete-event library Simkit. It has been shown that UAVSim can be used to determine values of parameters to enhance performance, determine if enhancement is possible, and also determine the point of diminishing return. Analysis also indicated that specification of only a mean value for MTBMAF in the ORD might not be sufficient for reliable performance. In addition, this model can be used for analysis of alternatives. This feature offers substantial benefit to SBA as it applies to UAVs. Lastly, UAVSim is scalable, expandable and reusable. It can be used throughout all phases of the acquisition process and beyond.

This thesis serves as a basis for follow-on studies involving the TUAV and other UAVs. Recommendations for model improvement and examples of follow-on studies have been provided.

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APPENDIX A. EXAMPLE MODEL OUTPUT FILES

Table A-1 shows an example of an input file which analysts can use to verify the inputs of the model. Table A-2 shows the output statistics file. A mean and user specified confidence interval is presented for each MOP.

```
SIMULATION Input data for \code\test1\1ie20maf.txt.out:
Number of platforms: 4
Number of maintenance paths: 1
Priority maintenance active: false
Wear and tear allowed on UAVs: false
Preventive Maintenance Effectiveness: 0.0
Maintenance constraints active: false
Number of maintenance teams: 1
Maximum number of platforms in flight :2
GCS constraints active: false
Number of GCS crews: 1
Length of Warm Up Period (days): 230.0000
Planned Length of Deployment (days): 5.0000
Actual Length of Simulation (days): 235.0000
OPTEMPO constraints active: false
Deployment OPTEMPO (hours): 12.0000
Surge OPTEMPO constraints active: false
Surge OPTEMPO (hours): 8.0000
Ingress time (hours): 1.0000
Egress time (hours): 1.0000
Scheduled on station time (hours): 4.0000
Platform turn time (hours): 0.5000
Time to complete scheduled maintenance (hours): 7.0000
Mean repair time for each non-mission affecting failures (hours): 0.5000
Flight time between scheduled maintenance actions (hours): 50.0000
Mean time between non-mission affecting failures (hours): 5.0000
The z value used to calculate confidence intervals: 1.9600

DISTRIBUTIONS and Parameters:
Platform MAF Time: Exponential
Platform MAF Time Parameters: 20.0
Sensor Package MAF Time: Exponential
Sensor Package MAF Time Parameters: 110.0
Platform Repair Time: Exponential
Platform Repair Time Parameters: 2.0
Sensor Package Repair Time: Exponential
Sensor Package Repair Time Parameters: 2.0
Logistics Delay Time: Exponential
Logistics Delay Time Parameters: 0.5
Preventive Maintenance Time: Exponential
Preventive Maintenance Time Parameters: 0.5
```

Table A-1: Example Input Data

```
\code\test1\1ie20maf.txt.stats
UAV Company Statistics

DEPLOYMENT Statistics:
Number of Days per Deployment: 235.0
Mean ETOS: 0.9048
Standard Deviation of ETOS (hours): 0.0069
Confidence Interval: 0.8913 - 0.9182

OPTEMPO Statistics:
OPTEMPO not used; not OPTEMPO Statistics

SORTIE Statistics:
Mean Number of Sorties per Deployment: 1481.4000
Standard Deviation for Sorties per Deployment: 10.1152
Confidence Interval for Sorties Per Deployment: 1461.5742 - 1501.2258

Mean Sortie Generation Rate (sorties/day): 6.3038
Standard Deviation for Sortie Generation Rate (sorties/day): 0.0430
Confidence Interval for Sorties Generation Rate: 6.2195 - 6.3882

MAINTENANCE Statistics:
Prioritization of Maintenance Active: false
Mean Wait Time in Maintenance Queue (hours): 1.7914
Standard Deviation of Mean Wait Time in Queue (hours): 0.0868
Confidence Interval for Mean Wait Time in Queue (hours): 1.6214 - 1.9615

Mean Time UAVs are Unavailable (hours): 3.2700
Standard Deviation of Mean Time UAVs are Unavailable (hours): 0.2230
Confidence Interval for Mean Time UAVs are Unavailable (hours): 2.8329 - 3.7071

Mean Amount Time UAVs Fly without Failures (hours): 5.1812
Standard Deviation for Amount of Time UAVs Fly without Failures (hours): 0.0394
Confidence Interval for Amount of Time UAVs Fly without Failures (hours): 5.1041 - 5.2584

Mean Time UAVs are Down for Maintenance (hours): 2.6408
Standard Deviation of Maintenance Down Time (hours): 0.0298
Confidence Interval for Maintenance Down Time (hours): 2.5825 - 2.6991

Mean Percentage of Scheduled Services: 0.1066
Standard Deviation of Mean Percentage of Scheduled Services: 0.0008
Confidence Interval for Mean Percentage of Scheduled Services: 0.1051 - 0.1082
```

Table A-2: Example Statistics Output File

APPENDIX B. VERIFICATION OF MOP NORMALITY ASSUMPTION

Figure B-1 shows a plot of the empirical and hypothesized CDFs for ETOS. The empirical CDF is represented by the blocked line and the hypothesized CDF is shown as the more smooth line.

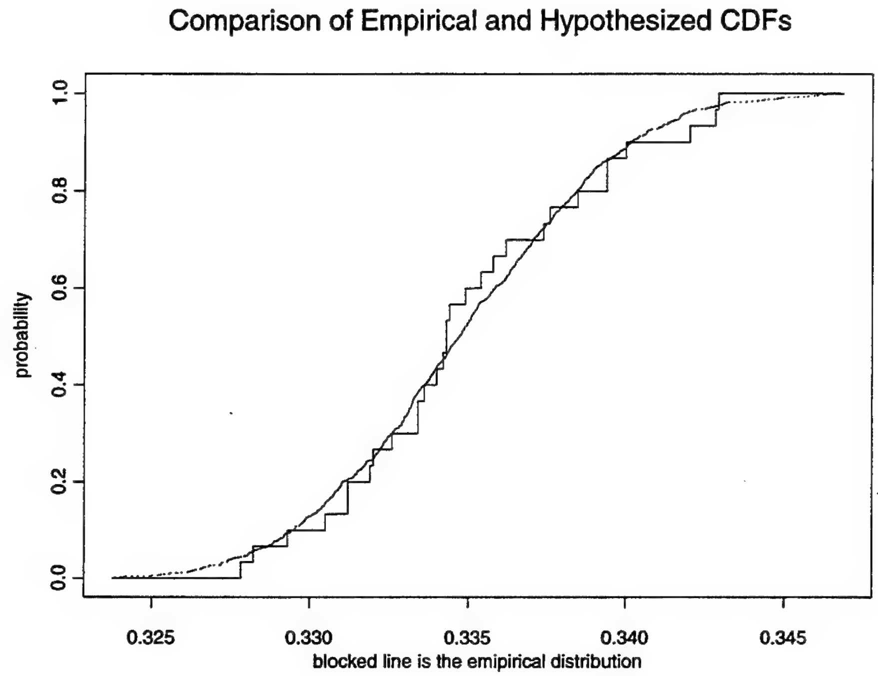

Figure B-1: Exploratory Plot of Normal CDFs

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APPENDIX C. GENERATION OF DISTRIBUTIONS

To allow for greater flexibility in selection of the distributions in UAVSim, Weibull and Lognormal distributions were constructed.

Weibull Distribution.

The distribution for Weibull variates was constructed using the inverse-transform algorithm. The algorithm for the Weibull was obtained from *Simulation Modeling and Analysis* [Ref. 26:p. 490].

Define U ~ uniform(0,1) as a random variate which is iid. The uniform(0,1) random variate was generated using a previously existing class in Simkit. The author assumed that the implementation of the algorithm to generate uniform(0,1) iid random variates to be correct.

1. generate U
2. return X, where $X = \beta(-\ln U)^{1/\alpha}$

The resulting values for X are Weibull variates and the observations are iid

Lognormal Distribution

The algorithm for the Lognormal was obtained from *Simulation Modeling and Analysis* [Ref. 26:p. 492].

Define Y~normal(μ,σ) random variate which is iid. The author assumes that the normal(μ,σ) distribution is implemented correctly.

1. generate Y
2. return $X = e^Y$

The resulting values for X are iid Lognormal random variates.

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APPENDIX D: EXAMPLES OF WEIBULL DISTRIBUTIONS

Figure D-1 shows the Weibull distributions that were used in this study. This example only illustrates distributions with a mean of twenty.

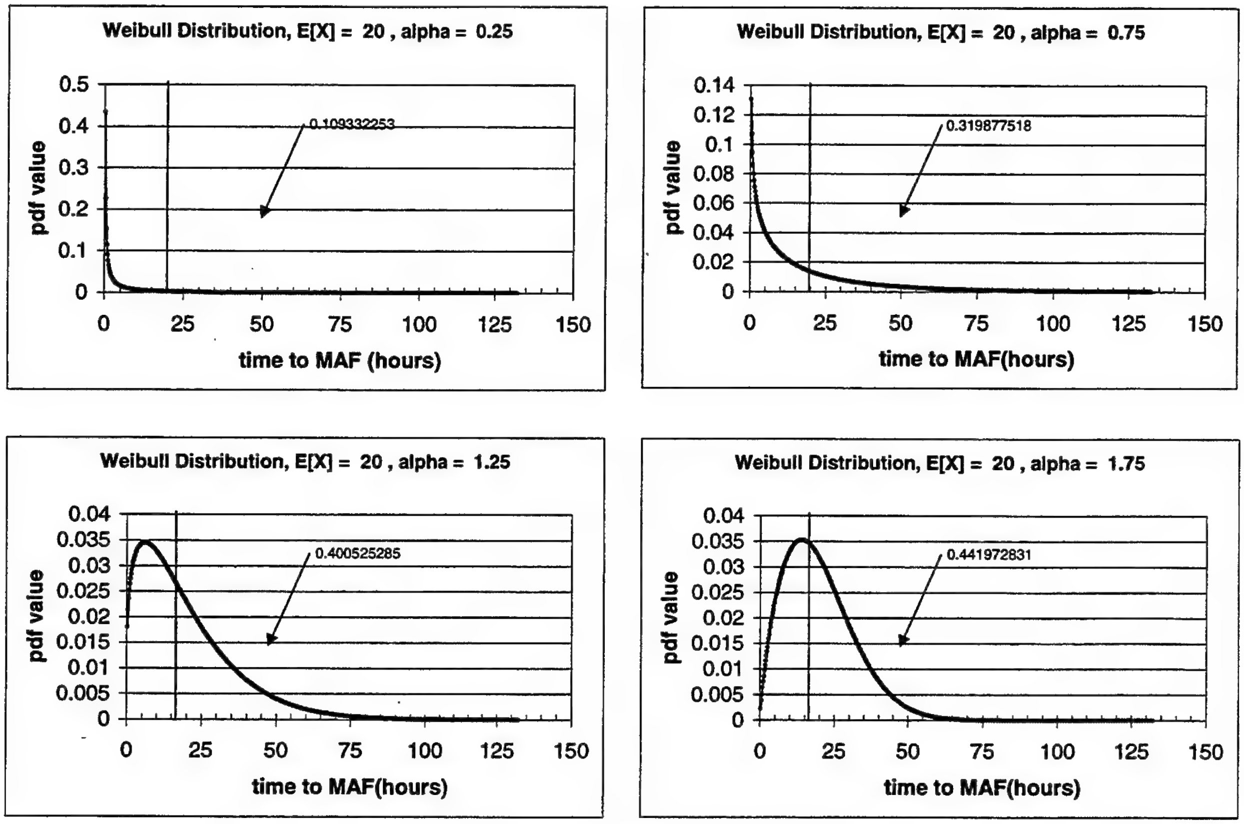

Figure D-1: Weibull Distributions

The proportion shown in each of the plots is the probability of surviving past the MTBMAF. This highlights the importance of not merely specifying the mean in the ORD.

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APPENDIX E: SCULPTURED AND TRIANGULAR DISTRIBUTIONS

Sculptured(a).

The algorithm for the Sculptured(a) distribution is:

Define U ~ uniform(0,1) random variate which is iid. The Uniform(0,1) random variate was generated using Simkit's random number generator.

1. generate U
2. return X, where $X = -\ln U*(1 + (\alpha * -\ln U))$
3.

The resulting values for X are Sculptured(a) variates and the observations are iid [Ref 22:p. 35].

Sculptured(b).

The algorithm for the Sculptured(b) distribution is:

Define U ~ uniform(0,1) random variate which is iid.

1. generate U
2. return X, where $X = -\ln U*(1 + (\alpha * -(\ln U)^3))$

The values for X are Sculptured(b) variates and the observations are iid [Ref 22:p. 35].

Triangular(a, b, c).

The algorithm for the Triangular distribution was verified as part of course work done at the Naval Postgraduate School. Diagnostic plots and a test for autocorrelation were done to verify that this algorithm worked properly as long as $a < c < b$.

define U1 ~ uniform(0,1) random variate which is iid.
define U2 ~ uniform(0,1) random variate which is iid.

```
1. generate U1 and U2
2. if (U1 < 1- (c-a)/(b-a)) {
     X = b - sqrt((a-b)^2 - U2(b-a)^2)
   }
   else {
     X = a + sqrt(U2(b-a))
   }
3. return X
```

The resulting variates are Triangular (a, b, c) and are iid.

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